Driving Performance After an Extended Period of Travel in an Automated Highway System

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FOREWORD

This report presents the results of one of a series of experiments that investigated driver performance in a generic Automated Highway System configuration. The experimental research was conducted in an advanced driving simulator and investigated the effects on normal driving of traveling under automated control for about 30 min. Traveling under automated control did not have an adverse effect on lane keeping and speed control. But, the minimum following distance and the minimum size of gaps rejected in lane incursions (incomplete lane changes) may have decreased as the result of automated travel. This report will be of interest to engineers and researchers involved in Intelligent Transportation Systems and other advanced highway systems.

Sufficient copies of the report are being distributed to provide a minimum of two copies to each FHWA regional and division office, and five copies to each State highway agency. Direct distribution is being made to division offices.

A. George Ostensen, Director
Office of Safety and Traffic Operations
Research and Development

NOTICE

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16. Abstract

The objective of this experiment—part of a series exploring human factors issues related to the Automated Highway System (AHS)—was to determine whether driving performance would be affected by extended travel under automated control at a velocity higher than the speed limit and closer to the vehicles ahead than usual. The experiment, conducted in the Iowa Driving Simulator, used a generic AHS configuration in which the left lane was reserved for automated vehicles. Unautomated vehicles traveled in the center and right lanes, the center lane was not a dedicated transition lane, and there were no barriers between the automated and unautomated lanes. Forty-eight drivers participated in the experiment—half were male, half were female; half were between the ages of 25 and 34 years, half aged 65 or older. Lane-keeping, speed control, following distance, lane-change, and incursion measures were used to compare driving performance before and after the drivers had traveled under automated control.

Results. (1) While it is not clear whether the experience of traveling under automated control produced the reductions in steering instability and velocity instability and the increased number of velocity fluctuations—all of which can be considered as improvements in driving performance—that were found for the drivers in the experimental group in the late data-collection period (since similar improvements were found for the drivers in the control group), it is clear that the experience of traveling under automated control did not have an adverse affect on lane keeping and speed control. (2) The minimum following distance and the minimum size of the rejected incursion gaps may have decreased for the drivers who traveled under automated control for an extended period of time, and they spent more time in the center lane both before and after they traveled under automated control. (3) The drivers who traveled under automated control expressed a preference for larger intra-string gaps than those that they experienced in this experiment. The drivers who were given control of both steering and speed simultaneously gave a significantly stronger positive response, when asked how they felt about the method of control transfer they used, than the drivers who first had to control speed, and then subsequently steering. (4) The smallest gaps for lane changes and incursions were similar—suggesting the minimum gap acceptable for a lane change is between 1.6 s and 2.4 s.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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SECTION 1. INTRODUCTION AND OVERVIEW

INTRODUCTION

Currently, a great deal of attention is being focused on the possibility of using advanced technologies to develop an Automated Highway System (AHS), which would allow hands-off/feet-off travel in one's own vehicle. Human factors issues related to potential implementation of an AHS are being explored in an ongoing, two-stage program that is being conducted for the Federal Highway Administration (FHWA). In the first stage of the program, seven experiments were conducted using the Iowa Driving Simulator. In the second stage, seven additional experiments were conducted, with the first five of them being run together. This report presents the results of the third, fourth, and fifth experiments of the second stage of the program.

The experiments reported here, like all those conducted in stage I, used an AHS configuration that would require little structural alteration to the roadways. It consists of a three-lane expressway in which the left-most lane is reserved for automated traffic that travels in strings of up to four vehicles, while the vehicles that remain under the control of their drivers travel in the center and right lanes. With this configuration, the center lane is also used by vehicles that are in the process of moving into or out of the automated lane—there is no dedicated transition lane to and from the AHS lane. Also, there are no barriers between the automated and unautomated lanes.

The experiments conducted in stage I of the program investigated the following:

- The transfer of control from the AHS to the driver of the simulator vehicle as the vehicle left the automated lane.(1)
- The transfer of control from the driver to the AHS as the simulator vehicle entered the automated lane.(2,3)
- The acceptability to a driver in the automated lane of decreasing vehicle separations as a vehicle entered the automated lane ahead of the driver.(4)
- The effectiveness of the driver when he/she was required to control the steering and/or speed when traveling through a segment of the expressway in which the capability of the AHS was reduced.(5)
- The effect on normal driving behavior after traveling under automated control for very brief periods of time.(6)

The first five stage II experiments were run together in a single combined experiment. These experiments examined:

- The behavior of the driver during the time that his/her vehicle was traveling under automated control (experiment 1).
- The kind of information that the driver wanted to have available when his/her vehicle was traveling under automated control (experiment 2).
- The effect on normal driving behavior after traveling under automated control for an extended period of time (experiment 3).
- The effect on normal driving behavior when different gap sizes between the driver's vehicle and the vehicle ahead during travel under automated control were used (experiment 4).
- The effect on normal driving behavior when different methods by which control was transferred from the automated system to the driver were used (experiment 5).

The results of the first two experiments are reported elsewhere.[7] The remaining three experiments, which all focus on the effect on normal driving behavior of traveling in an automated highway system, are addressed in this report.

THE EFFECTS OF TRAVELING IN AN AUTOMATED HIGHWAY SYSTEM

Two previous studies in this series of experiments provided some information about the possible carryover effects of traveling under automated control, although in both of those studies the drivers traveled under automated control for only brief periods of time.

In the first of these studies, Bloomfield, Buck, Carroll, Booth, Romano, McGehee, and North investigated the transfer of control from the AHS to the driver when the driver's vehicle was leaving the automated lane.[1] After traveling in the automated lane for 2 to 3 min, each driver resumed control of the simulator vehicle while it was still in the automated lane, traveling at the designated AHS velocity. On taking control, the driver was responsible for moving from the automated lane to the center lane. Bloomfield et al. found that the driver decelerated before moving the vehicle into the center lane, and that the velocity to which the driver decelerated varied as a function of the designated AHS velocity. When the designated AHS velocity was 104.7 km/h (65 mi/h), the driver reduced the speed of the vehicle to 91.5 km/h (56.8 mi/h) before moving from the automated lane to the center lane, i.e., the driver decelerated until the speed of the vehicle approximated the speed limit, which was 88.6 km/h (55 mi/h) in the unautomated lanes. In contrast, when the driver was reducing speed from the higher designated AHS velocities, the driver left the automated lane traveling at speeds that were considerably higher than the speed limit. When the designated AHS velocity was 128.8 km/h (80 mi/h), the driver left the automated lane at 104.4 km/h (64.9 mi/h), and when the designated AHS velocity was 153.0 km/h (95 mi/h) he/she left the automated lane at 109.8 km/h (68.9 mi/h).

The second study (Bloomfield, Christensen, and Carroll) directly investigated the effects on driving performance of brief periods of travel under automated control.(6) However, in this study, the driving-performance data equivalent to those obtained in the early study, i.e., driving-performance data obtained during the period in which the driver was decelerating immediately after leaving the automated lane, were not examined. Instead, the experiment focused on the driver's performance after he/she had achieved a stable cruising speed. Bloomfield, Christensen, and Carroll found that there was no decrement in steering performance after the driver had experienced a relatively limited amount of travel under automated control.(6) They also found that, although there was less velocity drift when the driver was in the center lane after traveling under automated control, there was more velocity instability and there were fewer velocity fluctuations. This means that, in order to maintain a chosen velocity before traveling in the AHS, the driver made more frequent, smaller velocity corrections. In contrast, in order to maintain a velocity after traveling in the AHS, the driver made less frequent, larger velocity corrections.(6) Bloomfield, Christensen, and Carroll suggested that traveling under automated control for an extended period may cause the driver to become less attentive to speed.(6) The current combined experiment explored this possibility.

As in the two earlier experiments, there was one experimental session for each driver in this experiment. However, in this session, there was only one trial. This trial lasted approximately 1 h, and in it the driver traveled in the automated lane for an extended period of time.

When the trial began, the driver's car was positioned on the entry ramp of an expressway. The driver's task was to drive into the right lane of the expressway, move to the center lane, and, when instructed, transfer control of the car to the automated system. On taking control, the AHS drove the simulator vehicle into the automated (left) lane and moved it to the last position in a string of automated vehicles. Then, the vehicle traveled under automated control for at least 35 min. During this period, the first two experiments were conducted: the behavior of the driver was videotaped, and various types of information about the trip and of potential interest to the driver were made available on a laptop computer mounted in the car.

Forty-eight drivers participated in the combined experiment: 36 were in the experimental groups and 12 were in the control group. The three combined experiments reported here investigated the effects on normal driving performance of traveling under automated control, varying the gap between the driver's car and the vehicle ahead, and varying the method by which control was transferred back to the driver. Driving-performance data were obtained in two data-collection periods, the first of which occurred relatively early in the trial, the second of which occurred relatively late. Table 1 shows the timeline for the two groups. For the drivers in both the control and experimental groups, the early data-collection period (which lasted 9.5 min) started after a 5-min practice driving period that began the trial. The late data-collection period lasted 9.0 min and started when drivers in the experimental group regained control of their vehicles after having been under automated control for at least 35 min.

Table 1. Trial timeline.

Length of Time	Experimental-Group Activity	Control-Group Activity
Trial start	Car on expressway entry ramp	Car on expressway entry ramp
9.5 min[a] **Early data-collection period**	Driver drove onto expressway, drove in right and center lanes	Driver drove onto expressway, drove in right and center lanes
About 1 min	AHS took control in center lane and drove car into left lane; car became last in a string	Driver drove in right and center lanes
At least 35 min	Car under automated control	Driver drove in right and center lanes
About 1 min	AHS drove car into center lane and released control to driver	Driver drove in right and center lanes
About 9 min **Late data-collection period**	Driver drove in center and right lanes	Driver drove in right and center lanes

[a] Minutes 0 through 5 were for driver practice; no data were analyzed for that time period.

While the driver's car was in the automated lane, it traveled at a velocity of 104.7 km/h (65 mi/h), i.e., 16.1 km/h (10 mi/h) faster than the speed limit in the unautomated lanes. During this period, the gap between the driver's car and the vehicle immediately ahead in the string of automated vehicles was much smaller than the following distances usually chosen by a driver in normal driving—gap sizes of 0.0625 s and 0.0344 s were used. In addition, three methods of transferring control from the AHS to the driver were investigated: (1) the driver gained control of the speed first and then steering control, (2) the driver gained control of the steering first and then speed, and (3) the driver gained control of the speed and steering simultaneously. Objective driving-performance data were collected during the periods of time that the driver was in control of the vehicle before and after traveling in the AHS. Subsequently, the pre-AHS and post-AHS data of the drivers in the experimental groups were compared with the driving-performance data obtained from the drivers in the control group to examine whether the experience of traveling in an automated lane had an impact on manual driving behavior.

OBJECTIVES OF THIS EXPERIMENT

The objectives of the combined experiments were:

- To determine whether driving behavior would be affected by traveling for an extended period of time under automated control at a speed greater than the speed limit and with a much-shorter-than-usual distance between the driver's car and the vehicle immediately ahead.
- To determine the effect on the driver's post-AHS behavior of varying the distance between the driver's car and the vehicle immediately ahead while the driver was traveling in the automated lane for an extended period of time.
- To determine the effect on the driver's post-AHS behavior of varying the method of transferring control from the AHS back to the driver as his/her vehicle left the automated lane.

To achieve these objectives, driving-performance data were obtained from the drivers in the experimental groups both before and after they traveled under automated control, and from the drivers in the control group in two data-collection periods that occurred early and late in the trial. The analyses of these data focused on the following experimental questions:

- *Does traveling under automated control for an extended period of time have an immediate effect on post-AHS driving performance?*

- *Does traveling under automated control for an extended period of time have a prolonged effect on post-AHS driving performance?*

- *Does the age of the driver affect the driver's performance after he/she has traveled under automated control for an extended period of time?*

- *Does the method of transferring control back to the driver after he/she has traveled in the automated lane for an extended period of time affect post-AHS driving performance?*

- *Does the gap between the vehicle ahead and the driver's vehicle (i.e., intra-string gap), while traveling in the automated lane for an extended period of time, affect post-AHS driving performance?*

SECTION 2. METHOD

SUBJECTS

Forty-eight drivers participated in this study. Twenty-four drivers were between the ages of 25 and 34. The remaining 24 drivers were at least 65 years old, with 12 between 65 and 69, and 12 age 70 or older. Half of the drivers in each age group were male, and half were female. The drivers were volunteers recruited through advertisements in the Iowa City and University of Iowa daily newspapers who met the following selection criteria:

- They had no licensing restrictions, other than wearing eyeglasses for vision correction during driving.
- They did not require special driving devices (the simulator is not equipped for such devices).
- They were medically screened to ensure good physical and mental condition.

Thirty-six drivers, 18 younger and 18 older, were assigned to the experimental groups. The remaining six younger and six older drivers were assigned to the control group.

THE IOWA DRIVING SIMULATOR

The Iowa Driving Simulator, located in the Center for Computer-Aided Design at the University of Iowa, Iowa City, is shown in figure 1.(8) The physical configuration consists of a domed enclosure mounted on a hexapod motion platform. The hexapod motion system employs 3.7-m- (60-inch-) stroke hydraulic actuators to induce six-degree-of-freedom motion cues to the driver. The motion system is capable of inducing correlated motion up to 5 Hz, vibration noise up to 8 Hz, and accelerations exceeding 1.0 *g*.

In this experiment, a Ford Taurus sedan was mounted on the motion platform, and the simulator was controlled by a computer complex that included a Harris Nighthawk 5800 and an Evans and Sutherland ESIG 2000 Computer Image Generator (CIG). The Nighthawk was controlled by the ICON operating system.(9) The Nighthawk was responsible for arbitrating subsystem scheduling and performing motion control, data-collection operations, instrumentation, control loading, and audio cue control. It also performed the multibody vehicle dynamics and complex scenario-control simulation.

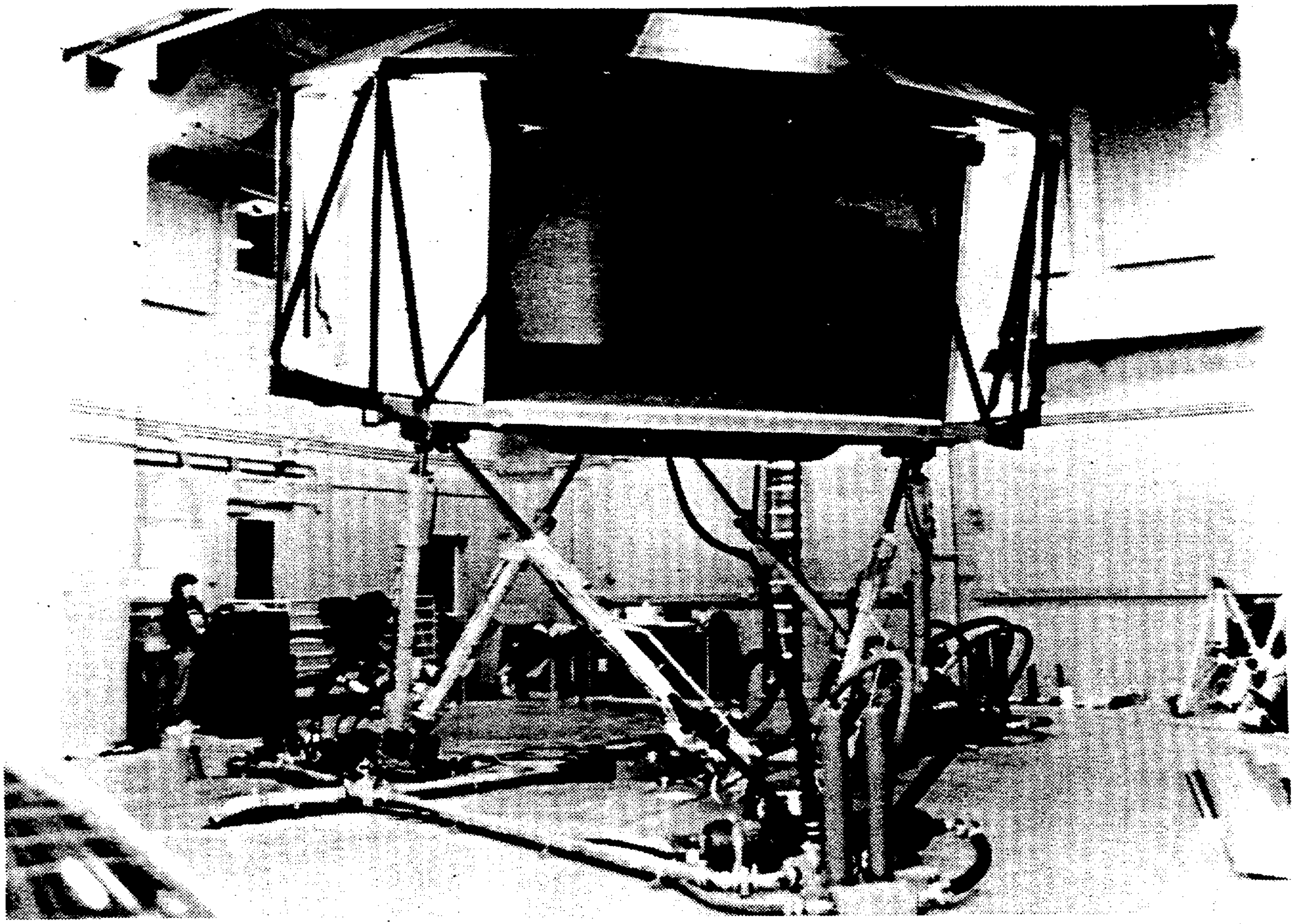

Figure 1. The Iowa Driving Simulator.

The inner walls of the dome act as a screen. For the current experiment, the correlated images generated by the CIG were projected onto two sections of these walls: one a 3.32-rad (190°) section in front of the simulator vehicle, the other a 1.13-rad (65°) section to its rear. The driver of the simulator vehicle viewed the images shown on the forward section through the windshield and side windows, and the images projected to the rear through an interior rear-view mirror, through a left side exterior driving mirror, or by turning around and looking through the back window.

DATA-COLLECTION PERIODS

Driving-performance data were obtained from 48 drivers, each of whom traveled on a simulated journey of approximately 1 h. The experience of the drivers in the experimental groups was considerably different from that of the drivers in the control group. For the 36 drivers who were in the experimental groups, the journey was divided into three sections: a pre-AHS, an AHS, and a post-AHS portion. The remaining 12 drivers, who were in the control group, retained control of the vehicle throughout the journey. Table 2 shows the timeline for the two groups.

The first 5 min of the journey were treated as practice for all 48 drivers—no driving-performance data were collected in this period. Then, at the beginning of the sixth minute of the trial, the first driving-performance data collection began: this was the early data-collection period. For the drivers in the experimental group, these pre-AHS driving-performance data were collected from the beginning of the sixth minute until the AHS issued a message requesting the driver to move into or stay in the center lane. Driving-performance data were collected from the drivers in the control group for the same time period.

Then, in the central portion of the trial, for the drivers in the experimental groups the simulator vehicle was in the automated lane under the control of the AHS for at least 35 min. For the drivers in the control group, the central portion of the trial lasted for 35 min, but they remained in control of their vehicles throughout this period.

Table 2. Trial timeline.

Length of Time	Experimental-Group Activity	Control-Group Activity
Trial start	Car on expressway entry ramp	Car on expressway entry ramp
9.5 min[a] **Early data-collection period**	Driver drives onto expressway, drives in right and center lanes	Driver drives onto expressway, drives in right and center lanes
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At least 35 min	Car under automated control	Driver drives in right and center lanes
About 1 min	AHS drives car into center lane and releases control to driver	Driver drives in right and center lanes
About 9 min **Late data-collection period**	Driver drives in center and right lanes	Driver drives in right and center lanes

[a] Minutes 0 through 5 were for driver practice; no data were analyzed for that time period.

In the final portion of the journey, the late data-collection period, driving-performance data were again collected. For the drivers in the experimental groups, these post-AHS driving-performance data were collected from the time that complete control of the simulator vehicle had been transferred from the AHS back to the driver. This transfer of control began approximately 10 min before the end of the trial and took approximately 60 s to complete. So, for the drivers in the experimental groups, the late data-collection period was approximately 9 min long. For the drivers in the control group, the second data-collection period began at the beginning of the 52nd minute and ended at the end of the 60th minute.

DRIVING SITUATION

The driving situation for the combined experiment can be described using the taxonomy of interactions between the driver and the AHS developed by Bloomfield et al.[(1)] Each driver drove in dry weather conditions, at midday, on a three-lane expressway. The route was 96.6 km (60 mi) long. A map of this route is presented in appendix 1. It contained 12 left curves and 8 right curves, all of which were 1.57-rad (90°) constant-radius curves. The radius of each curve was 762.5 m (2500 ft) and the superelevation was 0.04. The left lane was automated, the center and right lanes were unautomated, there was no transition lane, and there were no barriers between the automated and unautomated lanes. The lane widths were the current recommended minimum 3.7-m (12-ft) expressway width, and a standard road surface was used.

All the automated vehicles involved in the experiment were directly controlled by the AHS. When the driver's vehicle was under AHS control, the vehicle's steering wheel reflected the steering input from the AHS, the accelerator pedal reflected the throttle control by the AHS, and the brake pedal was disconnected.

The posted speed limit in the unautomated lanes was 88.6 km/h (55 mi/h). In the center and right lanes, the average velocity of the unautomated vehicles was 88.6 km/h (55 mi/h). The traffic density in the unautomated lanes was 12.42 v/km/ln (20 v/mi/ln). This traffic density level is close to the upper boundary of the Transportation Research Board Level of Service B (LOS B).[10] At this density, traffic flow is stable but the presence of other vehicles is noticeable and there is a slight decline in the freedom to maneuver; the mean headway time for vehicles in the unautomated lanes was 3.3 s. [Note: Mean headway time is the difference in arrival time of two consecutive vehicles at a particular observation point on the highway. It includes both the length of the first vehicle and the gap between it and the following vehicle.] The distribution of the velocities of the unautomated vehicles was normal, while a Pearson Type III distribution was used to generate the time headways. The method used to generate vehicles in this experiment is described in detail by Bloomfield et al.[1] The parameters used in the equations, defining both the normal distribution of velocities and the Pearson Type III distribution were derived using the procedure described by May and using the data provided by May.[11,12]

For the drivers who were in the experimental groups, in the first portion of the trial the driver controlled the simulator vehicle, driving for at least 15 min in the right and center lanes of the expressway. After this, control of the vehicle was transferred to the AHS. Then, in the second portion of the trial, which lasted at least 35 min, the driver's vehicle was under automated control, traveling most of that time in the AHS (left) lane. During this portion of the trial, each driver was able to use a laptop computer that provided various types of information, including the current location of the vehicle, the traffic conditions ahead, the estimated travel time to the destination, and the next exit and the distance to it (more details of this aspect of the combined experiment are given by Levitan and Bloomfield[7]). Then, in the third section of the trial, the drivers in the experimental groups again controlled the vehicle, this time driving for approximately 10 min in the center and right lanes.

For the drivers who were in the control group, there was no way to differentiate among the three portions of the trial. As far as these drivers were concerned, they simply drove in the expressway for 1 h. However, driving-performance data were obtained from these drivers early and late in the trial, at times that corresponded to the times at which data were collected from the drivers in the experimental groups, i.e., the first set of data were collected from the control-group drivers between the beginning of the 6th minute and the end of the 15th minute of the trial, while the second set of data were collected between the beginning of the 51st minute and the end of the 60th minute of the trial.

A strip map that indicated all the exits that the driver could encounter by name (e.g., County Road F) and number (e.g., Exit 24) was placed on the front passenger's seat of the car for only the experimental group. The distances between exits were not shown on the map. No instructions were given regarding the map, which is shown in appendix 1. The driver was free to use it whenever he/she wished.

EXPERIMENTAL DESIGN

Four independent variables were investigated. The first was a within-subjects variable that involved comparing the driving-performance data that were obtained in two data-collection periods: one that occurred early in the trial, the other that occurred late in the trial. The second independent variable, the age of the driver, was a between-subjects variable that could have affected the driver's performance in both data-collection periods. The remaining two variables were also between-subjects variables. But, unlike the age of the driver, they could only affect driving performance in the post-AHS segment of the trial. The reason for this was that the two variables, the intra-string gap and the method of transferring control from the AHS back to the driver, were not experienced by the driver until after he/she had traveled in the automated lane. Because of this, it was not expected that the main effect of either of these variables would be statistically significant. If either the intra-string gap or the control transfer method (described in the eponymous section below) had an effect, it was expected to be in an interaction with the pre- and post-AHS variable.

Data-collection period

Driving-performance data were collected in two data-collection periods: the first was a 9.5-min period that, for all drivers, began at the beginning of the sixth minute of the trial; the second was a 9.0-min period that, for the drivers in the experimental groups, began as soon as they regained control after traveling in the automated lane, and ended 9.0 min later, and, for the drivers in the control group, began at the beginning of the 52nd minute of the trial and finished at the end of the 60th minute.

Age of the Driver

The 60 drivers who took part in the current experiment were from two age groups. The first group consisted of drivers between 25 and 34 years of age, while the drivers in the second group were age 65 or older. There were 24 drivers in each group. To ensure that they represented the populations from which they were drawn, both groups were balanced for gender: half of the drivers in each group were male and half were female. In addition, to ensure that the ages of the older drivers did not cluster around the lower limit for the group, 12 of them were between 65 and 69 years of age and 12 were age 70 or older.

Intra-String Gap

After driving in the right and center lanes for approximately 15 min, the driver transferred control of the simulator vehicle to the AHS. The transfer of control occurred while the vehicle was in the center lane. The AHS moved the vehicle into the automated lane, increased its velocity, and positioned it at the end of the string of vehicles immediately ahead. After the driver's car had been under the control of the AHS for approximately 35 min, control was transferred back to the driver. Before relinquishing control, the AHS detached the simulator vehicle from the string of vehicles, by decreasing its velocity, and moved it into the center lane. Except during these two transitions, the driver's vehicle was in the automated lane, as the last vehicle in a string, throughout the period of time it was controlled by the AHS. The distance between the front bumper of the driver's car and the back bumper of the vehicle ahead took one of two values: for half of the drivers, this distance, the intra-string gap, was 0.0625 s (this was the smallest intra-string gap that was used in the stage I experiments); for the other half of the drivers, the intra-string gap was, at 0.0344 s, even shorter. Since the designated AHS velocity was 104.7 km/h (65 mi/h), the distance between the driver's car and the vehicle ahead was 1.8 m

(6.0 ft) when the intra-string gap was 0.0625 s, and 1.0 m (3.3 ft) when the intra-string gap was 0.0344 s.

Control-Transfer Method

After traveling under automated control for at least 35 min, control of the simulator vehicle was transferred back to the driver. While the vehicle was still in the automated lane, the AHS notified the driver that the vehicle would leave the automated lane in 30 s. After 30 s had passed and a suitable gap occurred between two unautomated vehicles in the center lane, the AHS reduced the speed of the vehicle to 88.6 km/h (55 mi/h), detached it from the string of vehicles, and moved the vehicle into the center lane. Once the vehicle was in the center lane, the AHS informed the driver how to take control of the vehicle in one of three ways:

- Speed first. With this method, the AHS first issued a message instructing the driver to take control of the speed of the vehicle by pressing down the brake or accelerator. Then, when the driver had control of the speed, the AHS issued a second message, which instructed the driver to take control of the steering by taking hold of the steering wheel. As soon as the driver was holding the steering wheel, the AHS issued a third message stating that the driver now had full control of the vehicle. If the driver failed to take control of either function within 15 s after the message was issued, the message was repeated. If the driver failed to take control of the function within 15 s of the third instance of the message, the simulation was stopped and the experiment ended.

- Steering first. With this method, the AHS first issued a message instructing the driver to take control of the steering by taking hold of the steering wheel. As soon as the driver was holding the steering wheel, the AHS issued a second message that instructed the driver to take control of the speed by pressing down the brake or accelerator. When the driver pressed the brake or accelerator, the AHS issued a third message stating that the driver now had full control of the vehicle. If the driver failed to take control of either function within 15 s after the message was issued, the message was repeated. If the driver failed to take control of the function within 15 s of the third instance of the message, the simulation was stopped and the experiment ended at that point.

- Speed and steering simultaneously. With this method, the AHS issued a message instructing the driver to take full control of the vehicle by holding the steering wheel and then pressing down the brake or accelerator. As soon as the driver had taken both of these actions, the AHS issued another message, which stated that the driver now had full control of the vehicle. If the driver failed to take control within 15 s after the message was issued, the message was repeated. Then, if the driver failed to take control within 15 s of the third instance of message, the simulation was stopped and the experiment ended at that point.

With all three methods, the system provided the opportunity for the driver to take control, but control was not released until the driver actively took control. The simulation was not stopped for any subject for failing to take control of the car.

Assignment of Drivers and Treatment of the Control Group

To determine the effects of 4 independent variables using 48 drivers, it was necessary to conduct 2 separate sets of analyses. Both sets used the same data, each analyzing the effects of three of the variables while collapsing the data across the fourth. Two of the variables were common to both sets of analyses. The data obtained in the early and late data-collection periods were compared and the effects of the age of the driver were explored by both sets.

In addition, the first set of analyses investigated the effects of varying the intra-string gap (collapsing the data across the methods of transferring control). If any analysis in this first set were to indicate that there was a statistically significant intra-string gap effect, this could be for one of two reasons: because there was, in fact, a difference in the performance of the drivers in the two intra-string-gap conditions, or because there was a difference in performance between the drivers who were in the control group and the experimental-group drivers (who experienced the different intra-string gaps).

The second set of analyses investigated the effect of varying the method of transferring control back to the driver (collapsing the data across the intra-string gaps). If any analysis in this second set were to indicate that there was a statistically significant effect of the method of transferring control, this, too, could be for one of two reasons: because there were, in fact, differences in the performance of the drivers in the three control-transfer-method conditions, or because there was a difference in performance between the drivers who were in the control group and those who were in the experimental group (and had experienced the different transfer methods).

For the analysis investigating the effect of varying the intra-string gap, the 48 drivers who took part in the experiment were divided into the 6 groups shown in table 3. Nine drivers were assigned to each of the four combinations of driver's age and intra-string gap, while there were six older and six younger drivers who were controls.

Table 3. Number of drivers for each combination of intra-string gap and the age of the driver.

	Driver Age	
Intra-String Gap	25 Through 34	65 and Older
0.0344 s	9	9
0.0625 s	9	9
Control Group	6	6

For the second analysis, the 48 drivers were divided into the 8 groups shown in table 4. There were six drivers for each combination of driver's age and method of transferring control, as well as the six older and six younger drivers who were controls.

Table 4. Number of drivers in each combination of method of transfer and the age of the driver.

	Driver Age	
Control Transfer Method	25 Through 34	65 and Older
Speed First	6	6
Steering First	6	6
Speed and Steering Together	6	6
Control Group	6	6

The combination of intra-string gap and method of transferring control experienced by each of the 48 drivers is shown in appendix 2.

EXPERIMENTAL PROCEDURE

The combined experiment was divided into two sessions. In the first session, the drivers watched an introductory videotape, drove for one experimental trial in the Iowa Driving Simulator, and filled out a questionnaire. In the second session of the experiment, the driver's visual capabilities were assessed.

Introduction, Training, and Practice Procedure

Before the start of the experiment, each driver watched a videotape containing introductory material describing this research program and the AHS, and providing some interactive practice with the AHS interface and protocol. The driver was told that the experiment involved first driving in the simulator and then completing several vision tests and a questionnaire. The driver was informed that this experiment is part of an ongoing FHWA program that is exploring ways of designing an AHS, determining how it might work, and how well drivers would handle their vehicles in such a system. It was made clear that the experiment was a test of the AHS, not a test of the driver. The video then gave explanations of the subtasks for the experiment and provided details to the drivers on how to:

- Transfer control of the vehicle to the AHS on entering the automated lane.
- Obtain information about their journey using the laptop computer mounted in the vehicle.
- Regain control back from the AHS on leaving the automated lane.

Four different versions of this training video were prepared: one version for each of the three different methods of transferring control from the AHS back to the driver at the end of the automated section of the drive, and one version for the control-group drivers who did not experience automated travel. The narrations of these four versions of the training videos are presented in appendix 3.

The instructional section of the three videos prepared for the drivers who were to travel in the automated lane lasted 10 min. The fourth version of the video, produced for the drivers in the control group, required less detail and was 3 min in length. When the videos were presented to the drivers, who were seated in a driving buck, the volume was adjusted so that the AHS messages were precisely as loud in the video as they would be in the simulator vehicle. Before the training video was presented, the drivers were told to pay particular attention to the auditory messages, as they would be exactly what would be heard in the vehicle. Then, after the training video was complete, the driver was asked:

> "Did you have any difficulty hearing any of those messages?"

This procedure was adopted to ensure that each driver would be able to hear the messages when they were presented during the experimental trial.

After the instructional section of the videos, each version continued with a series of practice segments. The first of these segments contained subtask practices that dealt with transferring control to the AHS, using the laptop computer to obtain information about the drive, and transferring control back from the AHS to the driver. An example of a subtask would be pressing the brake pedal or accelerator pedal in response to a request from the AHS. There were three practice segments for each of these subtasks. If the driver responded correctly on the first two segments, the third was omitted. If the driver did not respond correctly twice in a row for a particular subtask, the three segments were repeated until the driver was able to accomplish this. Following the subtask practices, the videos concluded with three more segments that covered the whole task for the driver. As before, if the driver responded correctly on the first two trials, the third was omitted, and if more than three trials were required, the segments were repeated.

Pre-Experimental Simulator Procedure

The driver was taken to the Iowa Driving Simulator and seated in the driver's seat of the simulator vehicle. The driver was asked to put on the seat belt and adjust the seat and mirrors, and then was given instructions on how to use the simulator emergency button. The driver was made aware that the headlights of the vehicle were already switched on, and that the air conditioner, dome lights, turn signal, and radio were operational. The driver was told that, if for any reason he/she wanted to stop at any time during the drive, to simply say so and the operator would stop the simulation.

Experimental Procedure and Instructions I

Each driver drove the simulator vehicle for one extended trial that lasted approximately 1 h. At the beginning of the trial, the vehicle was parked on a freeway entrance ramp. The driver was instructed to drive into the right lane of traffic on the three-lane expressway. The driver then drove in the right lane and the center lanes for at least 15 min. The density of the traffic in these two lanes was 12.42 v/km/ln (20 v/mi/ln).

For the sake of completeness, the instructions description indicates places where noncompliance would have led to termination of the experiment for that subject. No subject was terminated for failing to comply with instructions.

The driver was told that the left lane was reserved for automated vehicles, and that if he/she drove into it, the following auditory warning would be heard:

> "You've entered the left lane. You're not authorized to be in the left lane. Return to the center lane immediately."

At 14.5 min after the start of the trial, in order to prepare for entry into the AHS, the driver received one of two auditory messages: one was given if the driver's vehicle was in the right lane, the other if it was in the center lane. If the driver was in the right lane, the message was as follows:

> "Please move to the center lane and, when you get there, wait for further instructions."

[It is to be noted that a tone preceded each presentation by the AHS of an auditory verbal message, and whenever an auditory message was presented by the AHS, the car's radio speaker was silenced during the entire time the message was being presented.]

Then, as soon as the driver moved to the center lane, the following message was presented:

> "Please remain in the center lane and wait for further instructions."

If the driver did not comply with this message within 10 s, it was repeated; if the driver did not comply with the message after three presentations, the following message was presented and the experiment ended:

> "Please pull over to the right shoulder and stop."

If the driver was already in the center lane 14.5 min after the start of the trial, the AHS issued the following message:

> "Please remain in the center lane and wait for further instructions."

If the driver did not comply, and left the center lane, the following message was presented:

> "Please move to the center lane and, when you get there, wait for further instructions."

If the driver did not comply with this message within 10 s, it was repeated; if the driver did not comply with the message after three presentations, the following message was presented and the experiment ended:

> "Please pull over to the right shoulder and stop."

When the driver's vehicle was in the center lane at least 15 min after the start of the trial, the AHS presented the following message:

> "To engage the automated system, push the *On* button now."

If the driver complied, by pressing the *On* button on the steering wheel, the following message was presented in an auditory manner:

> "Welcome to the Automated Highway System. Your vehicle is now controlled by the automated system. You will enter the automated lane in a moment."

If the driver did not press the *On* button, the message was repeated twice at 10-s intervals. If the driver still failed to comply 5 s after the second repetition, the driver was instructed by the AHS to pull over to the right shoulder and stop, and the experiment ended.

Throughout the preautomated portion of the trial, the simulator vehicle remained under the control of the driver.

AHS Experience

As soon as the driver pressed the *On* button, the AHS took full control of the simulator vehicle and drove it into the automated lane. It entered the lane between two strings of automated vehicles. Once in there, the AHS increased the velocity of the driver's car until it caught up to the string ahead. It then joined that string as the last vehicle.

A laptop computer located to the driver's right was automatically activated when the vehicle entered the automated lane. The driver, who was trained how to use the computer and what information was available on it, was able to use this computer to obtain various types of information (i.e., current location, traffic conditions ahead, the estimated travel time to the destination, and the next exit and distance to it) while the vehicle was in the automated lane (see the report by Levitan and Bloomfield for more details of this aspect of the combined experiment).[7] The simulator vehicle traveled under automated control for at least 35 min. It remained the last vehicle in the string throughout this period of time. The computer was automatically turned off at the end of the period of automated travel.

Experimental Procedure and Instructions II

For the sake of completeness, the instructions description indicates places where noncompliance would have led to termination of the experiment for that subject. No subject was terminated for failing to comply with instructions.

After traveling under the automated control for at least 35 min, control of the simulator vehicle was transferred back to the driver. While the vehicle was still in the automated lane, the AHS used the following message to notify the driver that the vehicle would leave the automated lane:

> "You will leave the automated lane in 30 seconds. Once in the center lane, you will be asked to resume control of your vehicle."

Then, when a suitable gap occurred between two unautomated vehicles in the center lane, the AHS reduced the speed of the vehicle from 104.7 km/h (65 mi/h) to 88.6 km/h (55 mi/h), detached it from the string of vehicles, and moved the vehicle out of the automated lane. Once the vehicle was in the center lane, the AHS informed the driver how to take control of the vehicle in one of three ways. The first method was to regain control of the speed of the vehicle first, then the steering. Twelve drivers regained control of the vehicle in this way. The transfer of control from the AHS to the these drivers began when they heard the following message:

> "To regain control of the speed, press the accelerator or brake pedal."

When the driver had pressed the brake or accelerator and regained control of the speed, the AHS issued a second message:

> "You now control the speed. To regain control of the steering, put your hands on the steering wheel."

As soon as the driver was holding the steering wheel, the AHS issued a third message stating:

> "You now have complete control of your vehicle."

If the driver failed to take control of either function within 5 s of the message being issued, the message was repeated. If the driver failed to take control of the function within 5 s of the third instance of either message, the simulation was stopped and the experiment ended at that point.

The second method was to regain control of the steering first, then the speed. There were also 12 drivers who regained control of the vehicle this way. The transfer of control from the AHS to these drivers began when they heard the following message:

> "To regain control of the steering, put your hands on the steering wheel."

When the driver had put his/her hands on the steering wheel, and regained control of the steering, the AHS issued a second message:

> "You now control the steering. To regain control of the speed, press the accelerator or brake pedal."

As soon as the driver had taken control of the speed as well as the steering, the AHS issued a third message stating:

> "You now have complete control of your vehicle."

If the driver failed to take control of either function within 5 s of the message being issued, the message was repeated. If the driver failed to take control of the function within 5 s of the third instance of either message, the simulation was stopped and the experiment ended at that point.

The third method was to regain control of the speed and steering simultaneously. As with the other 2 control transfer methods, 12 drivers regained control of the vehicle this way. The transfer of control from the AHS to these drivers began when they heard the following message:

> "To regain control of the vehicle, put your hands on the steering wheel and press the accelerator or brake pedal."

As soon as the driver had complied with both requirements—holding the steering wheel while pressing either the accelerator or the brake pedal—the AHS issued this message:

> "You now have complete control of your vehicle."

If the driver failed to take control within 5 s of the message being issued, the message was repeated. Then, if the driver failed to take control within 5 s of the third instance of the message, the simulation was stopped and the experiment ended at that point.

After regaining control of the vehicle in one of these three ways, the driver continued driving in the unautomated lanes for approximately 10 min, until the end of the drive.

Control Group

Each driver in the control group was informed that there was an automated lane, that he/she was not supposed to drive in it, and that if he/she did try to move into that lane a warning message would be issued. The driver was also told that the speed limit in these lanes was 55 mi/h.

Post-Experimental Procedure

After completing the trial, the driver returned to the subject preparation room. Once there, the driver was debriefed and asked to complete a questionnaire that contained questions dealing with the driving simulator, his/her drive in the simulator vehicle, the laptop information, and the AHS. There were four different versions of the questionnaire, one for each method of control transfer and one for control subjects. Copies of these questionnaires are presented in appendix 4. The first part of the experiment ended here.

The visual capabilities of the driver were assessed in the second part of the experiment. This was done simply to see whether any subject had an anomaly that would warrant taking a closer look at his/her data. Most of the drivers who participated in the experiment took a 5-min break before the second part of the experiment. A few drivers were unable to complete the visual testing on the same day, and they returned on a later date to complete it.

Vision testing was divided into two sections. In the first section, a standard set of vision tests was administered: far foveal acuity, near foveal acuity, stereo depth perception, color deficiencies, lateral misalignment, and vertical misalignment. In the second section, the spatial localization perimeter developed by Wall was used to determine the subject's reaction time and accuracy when detecting both static and dynamic peripheral stimuli.[13]

SECTION 3. RESULTS

FOCUS OF THE DATA ANALYSIS

The results of the visual testing did not reveal the need to treat any subjects' data differently from the others'.

The objectives of the combined experiments were: (1) to determine whether driving behavior would be affected by traveling for an extended period of time under automated control at a speed greater than the speed limit and with a much-shorter-than-usual distance between the driver's car and the vehicle immediately ahead, (2) to determine the effect on the driver's post-AHS behavior of varying the distance between the driver's car and the vehicle immediately ahead while the driver was traveling in the automated lane for an extended period of time, and (3) to determine the effect on the driver's post-AHS behavior of varying the method of transferring control from the AHS back to the driver as his/her vehicle left the automated lane. To achieve these objectives, driving-performance data were obtained before and after each driver traveled under automated control in the automated lane for an extended period of time. The analyses of these data focused on the following experimental questions.

- *Does traveling under automated control for an extended period of time have an immediate effect on post-AHS driving performance?*

- *Does traveling under automated control for an extended period of time have a prolonged effect on post-AHS driving performance?*

- *Does the age of the driver affect the driver's performance after he/she has traveled under automated control for an extended period of time?*

- *Does the method of transferring control back to the driver after he/she has traveled in the automated lane for an extended period of time affect post-AHS driving performance?*

- *Does the intra-string gap experienced by the driver while traveling in the automated lane for an extended period of time affect post-AHS driving performance?*

DATA ANALYSIS

To answer these questions, driving-performance data were obtained from 48 drivers who traveled on a simulated journey of approximately 1 h. For the 36 drivers who were in the experimental groups, the journey was divided into three sections: a pre-AHS, an AHS, and a post-AHS section. Pre-AHS driving-performance data were collected from these drivers from the beginning of the sixth minute until 14.5 min after the start of the trial, at which point the AHS issued a message requesting the driver to move into or stay in the center lane. Post-AHS driving-performance data were collected from the time that complete control of the simulator vehicle had been transferred back to the driver until the end of the trial, approximately 9 min later.

The remaining 12 drivers were in the control group. They retained control of the vehicle throughout the journey. Driving-performance data were collected from these drivers in two data-collection periods that occurred early and late in the trial: the early data-collection period started at the beginning of the 6th minute and finished at the end of the 50th minute of the trial, while the late data-collection period started at the beginning of the 51st minute and lasted until the end of the 59th minute.

Thirteen driving measures were collected from the drivers in the control and experimental groups during the two data-collection periods early and late in the trial. These measures are listed in table 5.

Because little is known about the effects on manual driving behavior of traveling under automated control, particularly after automated travel as long as that used in this experiment, it was believed that a fine-grained look at the data was the best approach. Consequently, the post-automated travel data (i.e., in the late data-collection period) were segmented into nine successive 1-min periods to provide an opportunity to catch both immediate-but-short-lived effects and more persistent effects. This segmentation scheme was used with the first six driving measures shown in table 5: the two lane-keeping measures and the four speed-control measures. Because for some measures a 1-min period would either produce no data or too little data to be meaningful, the segmentation scheme was not used with the other measures in table 5: minimum following distance, percentage of time in the right and center lanes, number of lane changes, minimum gap size accepted in a lane change, number of incursions, and size of gap rejected in an incursion.

Five of the six driving measures for which the segmentation scheme was appropriate were developed recently. Bloomfield and Carroll suggest that the driver's lane-keeping performance can be described in terms of a linear equation that is the line of best fit for a series of points along the track of a vehicle.(14) This equation describes the position of a vehicle relative to the center of the lane at any time. The two lane-keeping measures listed in table 5 are measures of the driver's steering ability that are derived from this equation. The *steering instability* is a measure of the variability in steering that occurs when the driver is maintaining his/her position in the lane. Mathematically, it is the variability (i.e., the residual standard deviation) of the track of the vehicle about the line of best fit. *Steering oscillations* occur whenever the track of the vehicle crosses the line of best fit. The frequency with which steering oscillations occur is measured by determining the number of times that the track of the vehicle crosses the line of best fit per minute.

Table 5. Driving-performance measures collected in the pre-AHS and post-AHS sections of the trial.

Lane-keeping measures	• Steering instability.[1] • Number of steering oscillations.[1]
Speed-control measures	• Average velocity. • Velocity drift.[1] • Velocity instability.[1] • Number of velocity fluctuations.[1]
Following-distance measure	Minimum following distance
Lane-change measures	• Percentage of time spent in the center lane. • Percentage of time spent in the right lane. • Number of lane changes. • Size of gap accepted in a lane change.
Incursion measures	• Number of incursions. • Size of gap rejected in a lane incursion.

[1] Driving-performance measures developed by Bloomfield and Carroll.(14) [A brief account describing the development of these measures is provided in appendix 5.]

Bloomfield and Carroll also suggest that the driver's ability to control the speed of his/her vehicle can be described using another linear equation that is the line of best fit for speed control.(14) Three of the four speed control measures listed in table 5 are derived from this equation. The *velocity drift* is a measure of the rate at which the velocity of the vehicle increases or decreases as a function of the distance traveled along the lane. It is the gradient of the line of best fit of the actual velocities of the vehicle (measured in this experiment) every one-thirtieth of a second. The *velocity instability* measures the variability in velocity that occurs when the driver is driving along the lane. Mathematically, it is the variability (i.e., the residual standard deviation) of the actual velocities of the vehicle about the line of best fit. *Velocity fluctuations* occur every time the plot of the actual velocities of the vehicle crosses the line of best fit. The frequency with which velocity fluctuations occur is measured by determining the number of times per minute that the line of best fit is crossed. [Further details of the derivation of these measures are presented in appendix 5.]

Average velocity, the fourth speed-control measure in table 5, gives an overall indication of the driver's speed. The remaining seven measures listed in table 5 are self-explanatory.

As noted above, two different analyses of variance (ANOVA's) were done on the dependent variables, each collapsing across one of the independent variables. The independent measures used in each analysis and their levels are shown in table 6. Note importantly that the control-group data are used as one of the levels of one of the independent variables in each analysis.

Table 6. Independent variables used in the two ANOVA's and their levels.

Independent Variable	Levels
Intra-String Gap Analysis (collapsed across control transfer methods)	
Age	25 through 34, 65 and older
Data-collection period	Early, late
Intra-string gap	0.0344 s, 0.0625 s, control group
Transfer-Method Analysis (collapsed across intra-string gaps)	
Age	25 through 34, 65 and older
Data-collection period	Early, late
Transfer method	Speed first, steering first, speed and steering simultaneously, control group

LANE-KEEPING PERFORMANCE

Two lane-keeping measures, the steering instability and the number of steering oscillations, are discussed in this section. Four ANOVA's were conducted: two for the steering instability and two for the number of steering oscillations. For both variables, the first ANOVA determined the effect on the driver's post-AHS driving performance of varying the intra-string gap. For this analysis, the data were collapsed over the methods of transferring control. The second ANOVA analyzed the effect of varying the method of transferring control, this time collapsing the data over the intra-string gaps. In both ANOVA's, data averaged over the entire early data-collection period were compared with data from each of the nine 1-min segments into which the late data-collection period was divided.

Steering Instability

The steering instability provides a measure of the variability in steering around the line of best fit of the track of the vehicle. The statistically significant effects found by the two ANOVA's conducted on these data are shown in table 7. The complete summary tables for these ANOVA's are presented in appendix 7.

Table 7. Summary of the statistically significant effects found in the ANOVA's conducted to determine if the steering instability or number of steering oscillations were affected by the data-collection period (D), the age of the driver, the intra-string gap (I), or the method of transferring control.

	Steering Instability		Number of Steering Oscillations	
Source	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]
D	0.0002	0.0001	–	–
I x D	0.0372	–	–	–

[a] Control group is one level of intra-string gap.

[b] Control group is one level of transfer method.

As can be seen from table 7, only one variable—the difference between the early and late data-collection periods—had a statistically significant effect. The other three independent variables did not produce significant differences. It should be noted that, since neither the intra-string gap nor the method of control transfer had a statistically significant effect, there was no evidence of a difference between the steering instability for the drivers in the experimental groups and the steering instability of the drivers in the control group. There was one statistically significant interaction, that between data-collection period and the intra-string gap.

Interaction Between Data-collection period and Intra-String Gap. The summary of the intra-string gap ANOVA, shown in table 7, reveals that there was a statistically significant interaction between data-collection period and intra-string gap. This interaction is illustrated in figure 2. It occurred because there was more steering instability for the drivers in the control group in four of

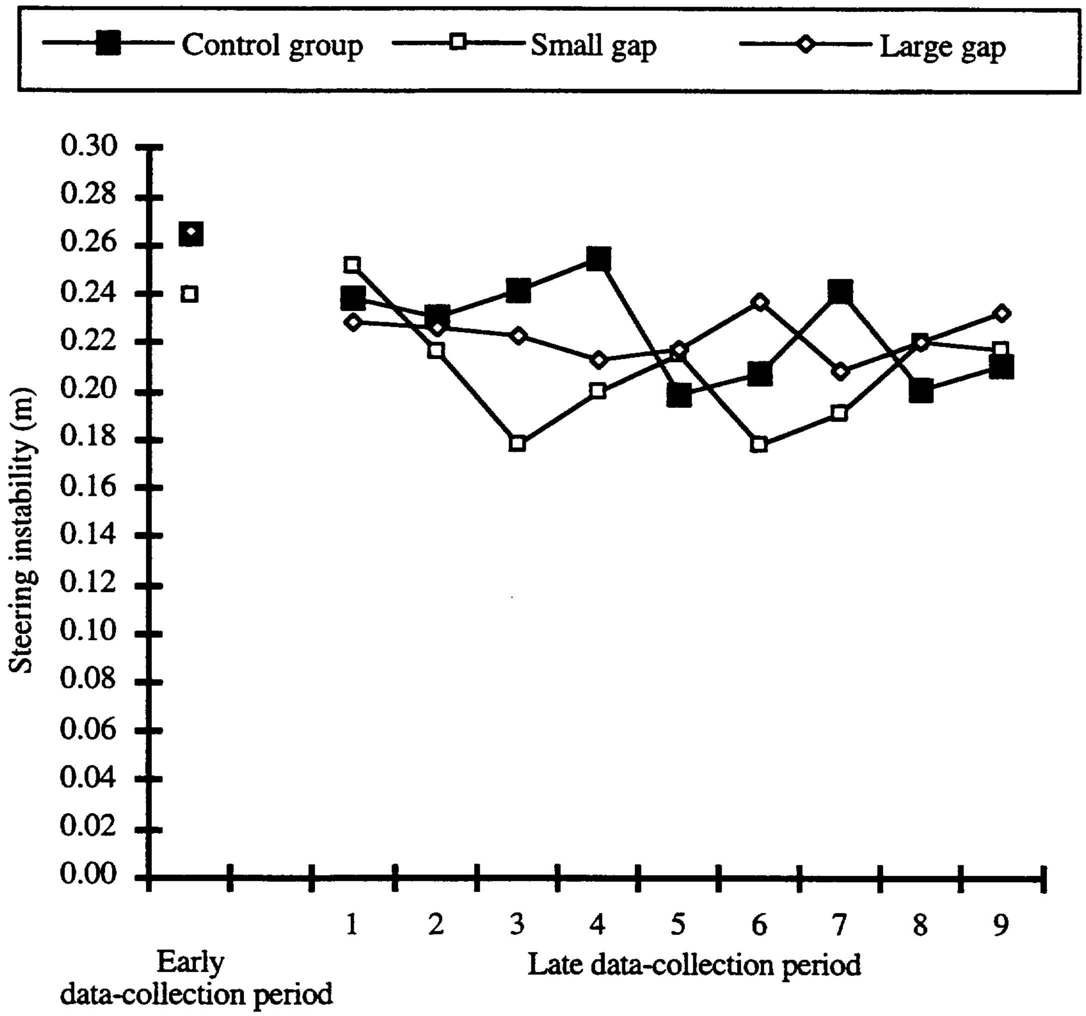

Figure 2. Comparisons of the mean steering instabilities in the early data-collection period and the nine 1-min segments in the late data-collection period of the drivers in the control group and the drivers in the small- and large-intra-string-gap groups.

the nine 1-min segments of the late data-collection period (the second, third, fourth, and seventh segments), more steering instability for the drivers who traveled under automated control with the large (0.0625-s) intra-string gap in four of the nine 1-min segments of the late data-collection period (the fifth, sixth, eighth, and ninth segments), and more steering instability for the drivers who traveled under automated control with the small (0.0344-s) intra-string gap in only one of the 1-min segments of the late data-collection period (the first segment).

Data-collection period. As can be seen in table 7, the summaries of the intra-string gap ANOVA and the transfer-method ANOVA both indicate that there were statistically significant differences in the steering instability means obtained in the early and late data-collection periods. [Note: Since the two ANOVA's analyzed the same data—one collapsing across transfer methods, the other across intra-string gaps—the steering instability means obtained in the early and late data-collection periods were the same in both ANOVA's.] The Tukey Studentized Range test was used to determine which steering instability means were significantly different; the results are shown in table 8.

As the first line in table 8 indicates, the mean steering instability in the early data-collection period was significantly different from the steering instability in seven of the nine 1-min segments of the late data-collection period (the exceptions were the first two 1-min segments of the late period). The table also shows that the mean steering instability in the first 1-min segment of the late period was significantly different from the steering instability in the sixth 1-min segment of the late data-collection period. These significant differences are illustrated in figure 3, which also shows that there was an overall decrease in steering instability from the early to the late data-collection period. To determine whether this decrease occurred for the drivers in the control and the experimental groups, it was first necessary to average the data for the drivers in the experimental groups over both the intra-string gap and the method of control transfer. Then, the drivers in the control and experimental groups were compared. The results are shown in figure 4.

Table 8. Results of all pairwise comparisons of average steering instability between the early data-collection period and each 1-min segment of the late data-collection period.[a]

		1-min Segment of the Late Data-Collection Period								
	Early Data-Collection Period	1	2	3	4	5	6	7	8	9
Early Data-Collection Period		–	–	*	*	*	*	*	*	*
1			–	–	–	–	*	–	–	–
2				–	–	–	–	–	–	–
3					–	–	–	–	–	–
4						–	–	–	–	–
5							–	–	–	–
6								–	–	–
7									–	–
8										–
9										

[a] "–" means the comparison was not significant; "*" means the comparison was significant at $p \leq 0.05$. Thus, the "-" at the intersection of "early data-collection period" and "1" indicates that there was no significant difference between pre-AHS average steering instability ("early data-collection period") and average steering instability in the first minute post-AHS ("1").

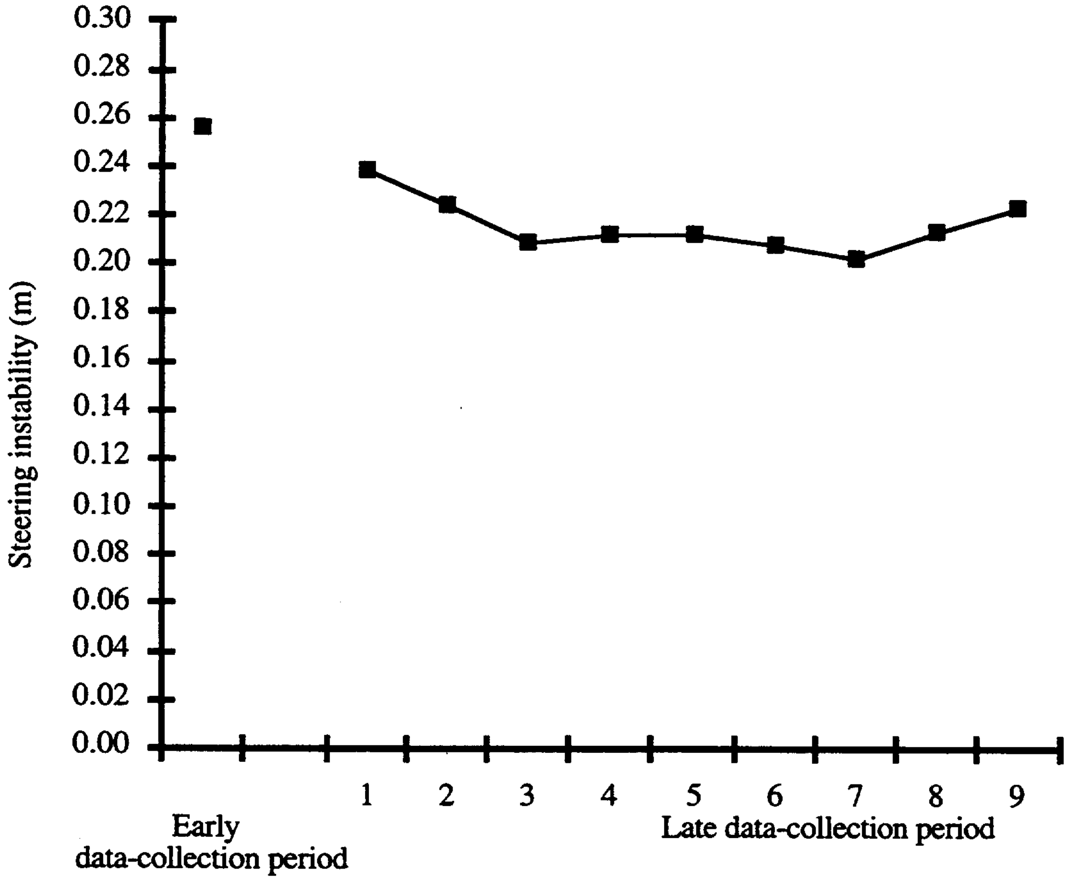

Figure 3. The mean steering instability in the early data-collection period compared with the mean steering instability in each of the nine 1-min segments in the late data-collection period.

Figure 4 confirms that the decrease in steering instability from the early to the late data-collection period occurred for the drivers in both the control and experimental groups. In addition, the figure illustrates—as can be inferred from the lack of a statistically significant difference (in table 7) in the steering instability means of the drivers in the control and experimental groups—that there was little difference in steering instability of the drivers in the control and experimental groups.

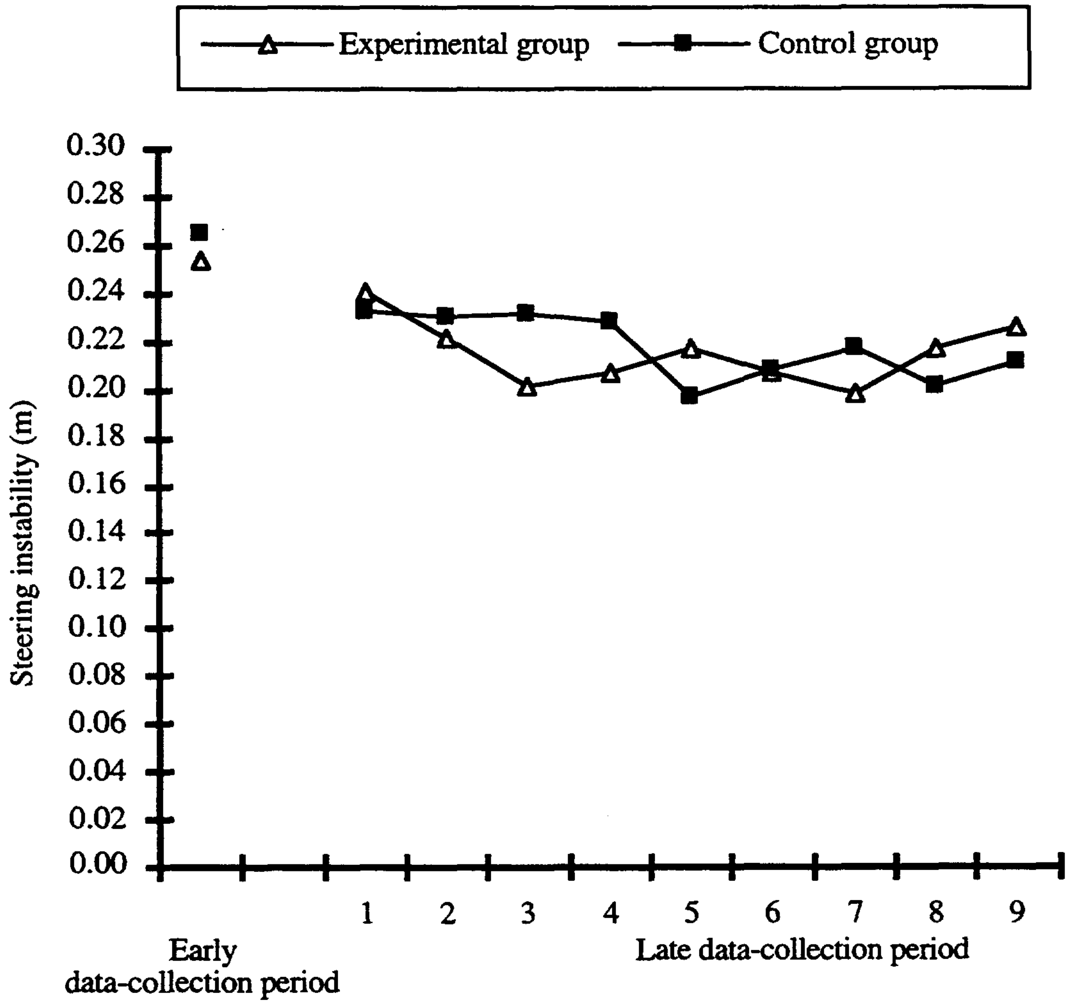

Figure 4. The mean steering instability in the early data-collection period compared with the mean steering instability in each of the nine 1-min segments in the late data-collection period for the drivers in both the control and experimental groups.

Number Of Steering Oscillations

Table 7 indicates that no statistically significant differences were found in the two ANOVA's that were conducted to determine whether the number of steering oscillations (i.e., the number of times the steering line of best fit was crossed per minute) was affected by which data period the data were collected in, the age of the driver, the intra-string gap, or the method of control transfer. The average number of steering oscillations across all variables was 13.3.

SPEED-CONTROL PERFORMANCE

The four speed-control measures investigated were the velocity drift, the velocity instability, the number of velocity fluctuations, and the average velocity. Two ANOVA's were conducted to determine whether these speed-control measures were affected by the data-collection period, the age of the driver, the intra-string gap, or the method of transferring control. The variables that were found to have statistically significant effects on the speed-control measures are listed in table 9. The complete summary tables for these eight ANOVA's are presented in appendix 7. As table 9 shows, there were no statistically significant interactions in any of the eight ANOVA's.

Table 9. Summary of the statistically significant effects found in the ANOVA's conducted to determine if the speed-control measures were affected by the data-collection period (D), the age of the driver (A), the intra-string gap, or by the method of transferring control.

	Average Velocity		Velocity Drift		Velocity Instability		Number of Velocity Fluctuations	
Source	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]
A	0.0160	0.0157	–	–	–	–	–	–
D	–	–	–	–	0.0001	0.0001	0.0001	0.0001

[a] Control group is one level of intra-string gap.

[b] Control group is one level of transfer method.

Both sets of analyses were conducted on the speed-control measures in order to determine whether the measures were affected by the data-collection period or by the age of the driver. In addition, the first analysis in each pair of ANOVA's indicated whether any of the four speed-control measures were affected by variations in the size of the intra-string gap, with the data collapsed over the methods of transferring control. The second analysis in each pair indicated whether the speed-control measures were affected by variations in the method of transferring control, with the data collapsed over the intra-string gaps.

As can be seen from table 9, the age of the driver had a statistically significant effect on the average velocity. However, the table also shows that no statistically significant effects were found for the velocity drift. For the remaining two speed-control measures, the velocity instability and the number of velocity fluctuations, statistically significant differences were found between the early and late data-collection periods. In addition, it should be noted that neither the intra-string gap nor the method of control transfer had a statistically significant effect on any of the four speed control measures. So, as with the lane-keeping measures, there was no evidence that there were differences between the drivers in the experimental groups and those in the control group. There were no statistically significant interactions.

Average Velocity

As table 9 indicated, only one variable, the age of the driver, had a statistically significant effect on the average velocity at which the drivers drove during the two data-collection periods. The other independent variables—the data-collection period, the intra-string gap, and the method of transferring control—and the interactions between them were not significant.

Age of the Driver. Table 9 indicated that the average velocity was affected only by the age of the driver. The effect is shown in figure 5. The younger drivers drove faster than the older drivers: on average, they drove at 87.5 km/h (54.3 mi/h) and 84.2 km/h (52.4 mi/h), respectively.

Velocity Drift

The velocity drift is the rate at which the velocity of the vehicle increases or decreases as a function of the distance traveled along the lane. Mathematically, it is the gradient of the line of best fit of the actual velocities of the vehicle. As can be seen in table 9, the velocity drift was unaffected by the data-collection period, the age of the driver, the intra-string gap, or the method of transferring control. In addition, none of the interactions were significant.

Velocity Instability

The velocity instability is the variability in velocity that occurs when the driver is driving along the lane. Mathematically, it is the variability (i.e., the residual standard deviation) of the actual velocities of the vehicle about the line of best fit. Table 9 shows that the data-collection period had a statistically significant effect on the velocity instability. However, the remaining three

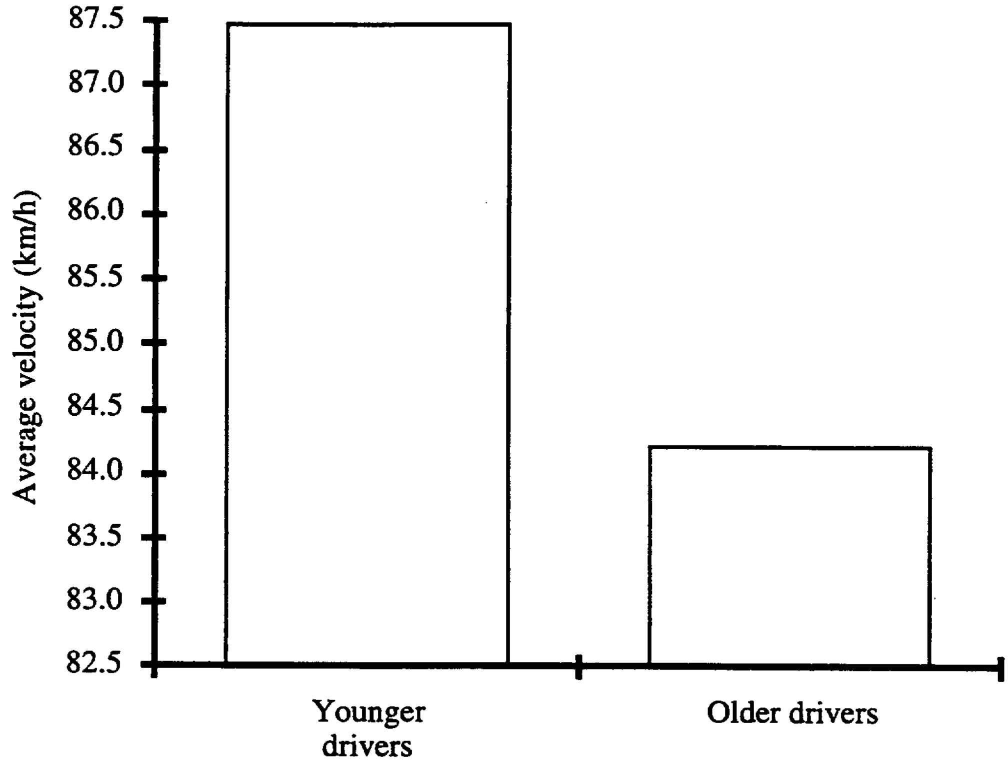

Figure 5. Mean velocity for older and younger drivers.

variables—the age of the driver, the intra-string gap, and the method of transferring control—did not affect the velocity instability. Also, none of the interactions were significant.

Data-collection period. The summaries of the intra-string gap ANOVA and the transfer-method ANOVA, which are shown in table 9, reveal that there were statistically significant differences in the steering instability means obtained in the early and late data-collection periods. The Tukey Studentized Range test was used to determine which steering instability means were significantly different; the results are shown in table 10.

The first line in table 10 shows that the mean velocity instability in the early data-collection period was significantly different from the steering instability in eight of the nine 1-min segments of the late data-collection period (the exception was the first 1-min segment of the late period). Similarly, the second line of table 10 indicates that the mean steering instability was significantly different in the first 1-min segment of the late period than it was in five of the remaining eight 1-min segments of that period. These significant differences are illustrated in figure 6.

Table 10. Results of all pairwise comparisons of average velocity instability between the early data-collection period and each 1-min segment of the late data-collection period.[a]

	Early Data-Collection Period	1-min Segment of the Late Data-collection period: 1	2	3	4	5	6	7	8	9
Early Data-Collection Period		–	*	*	*	*	*	*	*	*
1			*	*	*	*	–	*	–	–
2				–	–	–	–	–	–	–
3					–	–	–	–	–	–
4						–	–	–	–	–
5							–	–	–	–
6								–	–	–
7									–	–
8										–
9										

[a] "-"means the comparison was not significant; "*" means the comparison was significant at $p \leq 0.05$. Thus, the "-" at the intersection of "early data-collection period" and "1" indicates that there was no significant difference between pre-AHS average velocity instability ("early data-collection period") and average velocity instability in the first minute post-AHS ("1").

Figure 6 shows that there was more velocity instability in the early data-collection period than there was in the late period. It also appears from the figure that there was more velocity instability in the first 1-min segment of the late period than there was in the rest of that period, but the difference was statistically significant in only five of the eight cases.

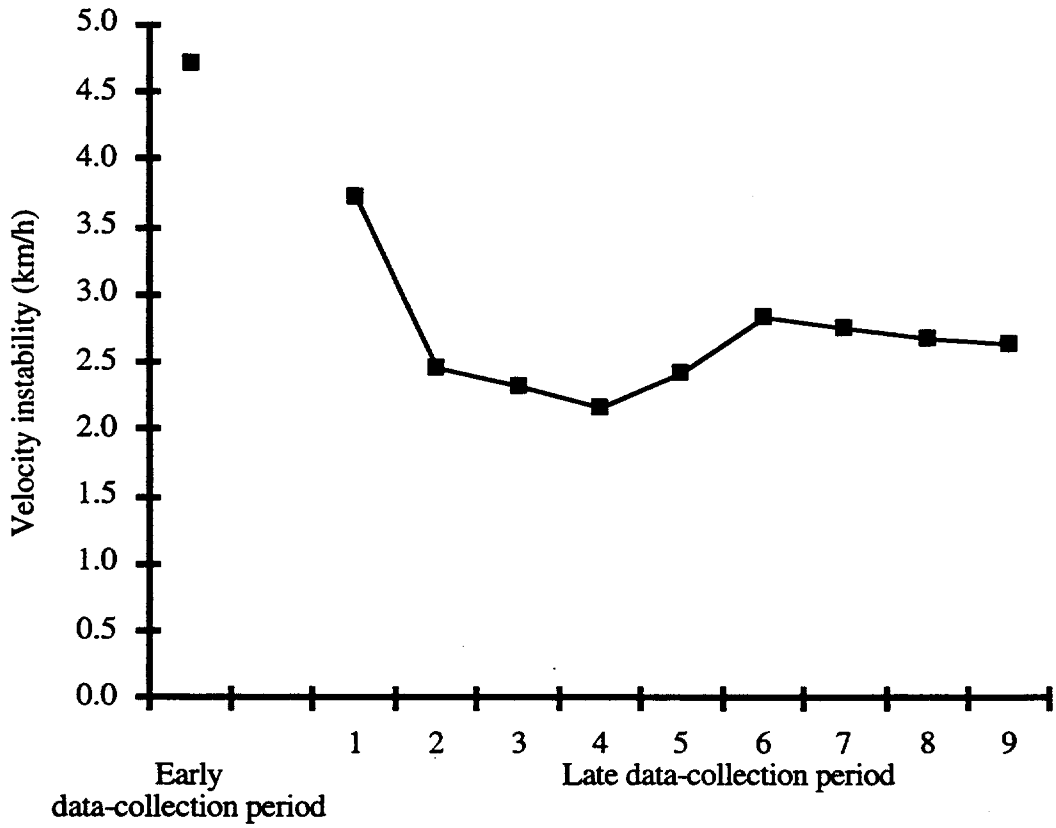

Figure 6. The mean velocity instability in the early data-collection period compared with the mean velocity instability in each of the nine 1-min segments in the late data-collection period.

Table 9 indicated that there was no statistically significant difference in velocity instability between the drivers in the control and experimental groups. Figure 7 shows that there was very little difference between the two groups of drivers. It also confirms the pattern, seen in figure 6, that there was a drop in velocity instability from the early data-collection period to the late period, and a drop from the first minute of the late period to the rest of that period.

The Number Of Velocity Fluctuations

The final speed-control measure is the number of velocity fluctuations (i.e., the number of times per minute that the plot of the actual velocities of the vehicle crosses the line of best fit). As shown in table 9, there was only one variable that had a statistically significant effect on the number of velocity fluctuations: as with the velocity instability, it was the data-collection period.

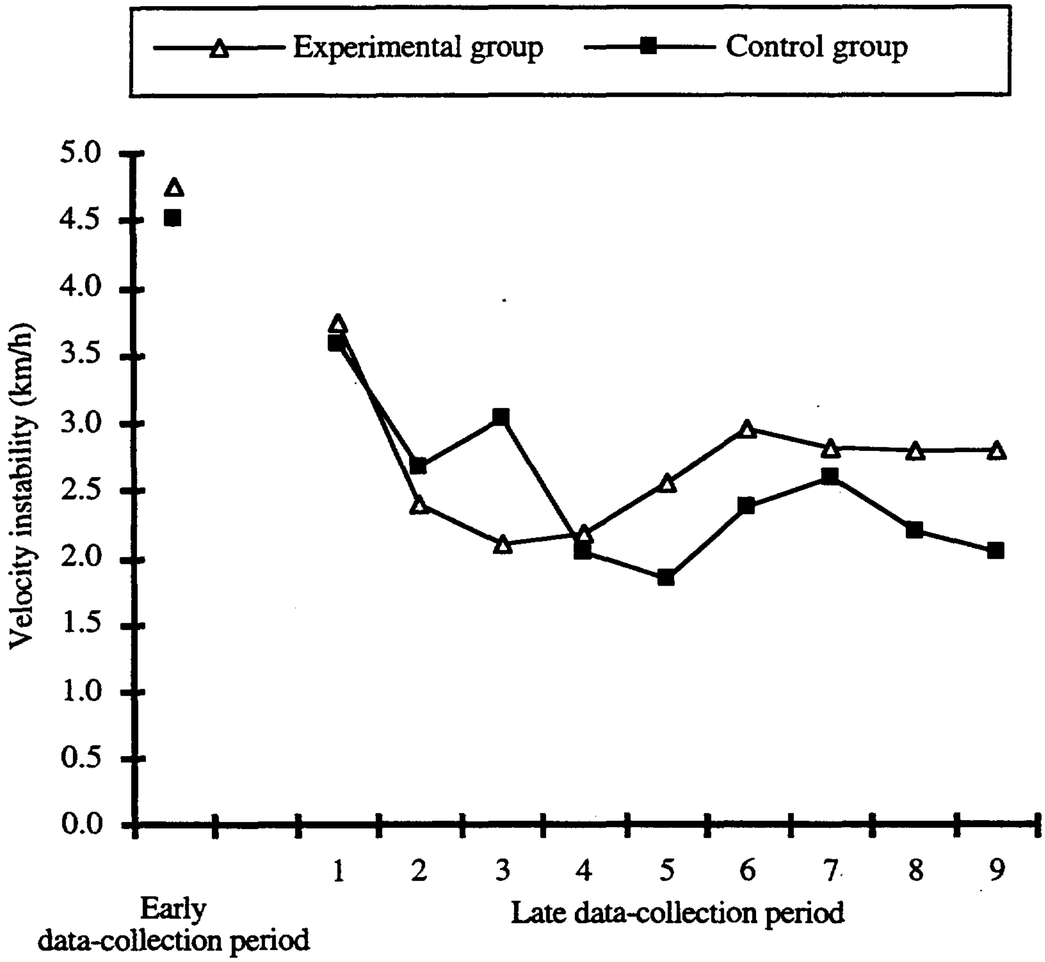

Figure 7. The mean velocity instability in the early data-collection period compared with the mean velocity instability in each of the nine 1-min segments in the late data-collection period for the drivers in both the control and experimental groups.

Data-collection period. The Tukey Studentized Range test was used to determine whether the mean number of velocity fluctuations in the early data-collection period was different from the number in any of the 1-min segments of the late data-collection period, and whether there were any differences in the number of velocity fluctuations among the 1-min segments. The results are shown in table 11.

Table 11. Results of all pairwise comparisons of average velocity fluctuations between the early data-collection period and each 1-min segment of the late data-collection period.[a]

	Early Data-Collection Period	1-min Segment of the Late Data-collection period								
		1	2	3	4	5	6	7	8	9
Early Data-Collection Period		–	–	*	*	*	*	*	*	*
1			–	–	–	–	–	–	–	–
2				–	–	–	–	–	–	–
3					–	–	–	–	–	–
4						–	–	–	–	–
5							–	–	–	–
6								–	–	–
7									–	–
8										–
9										

[a] "-"means the comparison was not significant; "*" means the comparison was significant at $p \leq 0.05$. Thus, the "-" at the intersection of "early data-collection period" and "1" indicates that there was no significant difference between pre-AHS average velocity fluctuations ("early data-collection period") and average velocity fluctuations in the first minute post-AHS ("1").

The first line in table 11 shows that the number of velocity fluctuations in the early data-collection period was significantly different from the number of fluctuations in seven of the nine 1-min segments of the late data-collection period (the exceptions occurred for the first and second 1-min segments). Figure 8 illustrates the effects. There were no statistically significant differences in the mean number of velocity fluctuations for any of the nine 1-min segments in the late data-collection period.

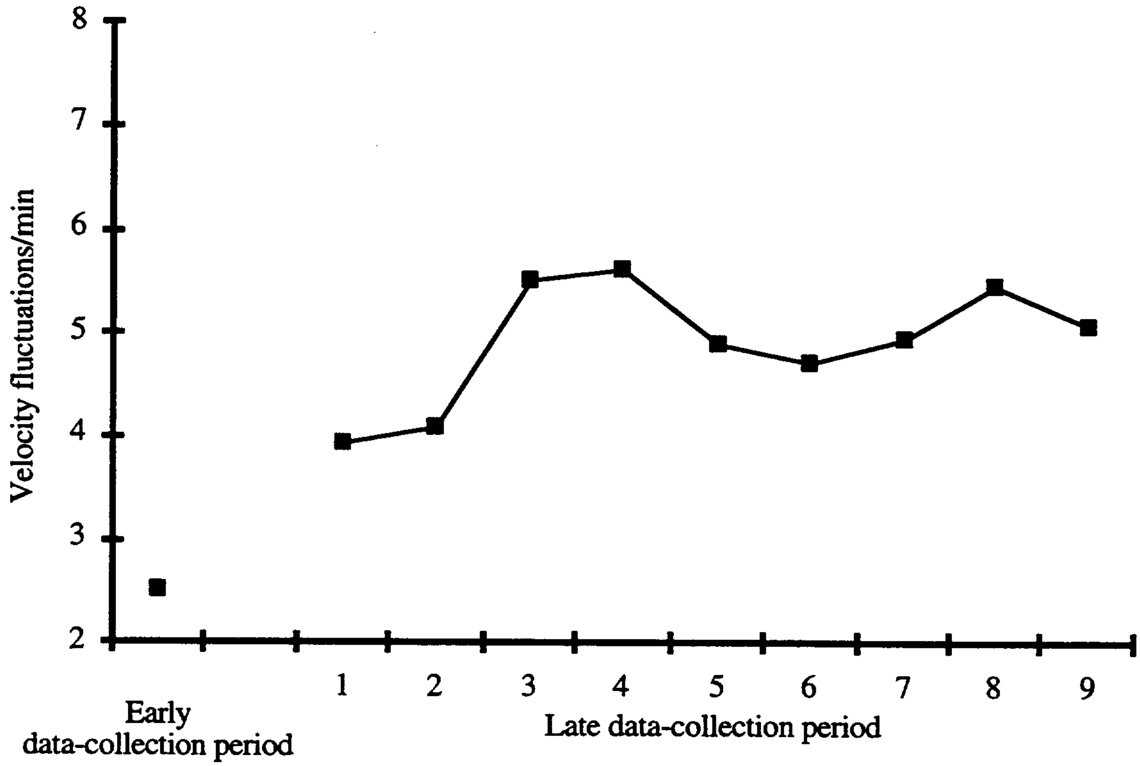

Figure 8. The mean number of velocity fluctuations in the early data-collection period compared with the mean number of velocity fluctuations in each of the nine 1-min segments in the late data-collection period.

Table 9 indicated that there was no statistically significant difference in velocity instability between the drivers in the control and experimental groups. The pattern seen in figure 8 (that of an increase in the number of velocity fluctuations from the early to the late data-collection period), as figure 9 shows, occurred for the drivers in both the control and experimental groups. It should be noted that, while figure 9 seems to indicate that there were more velocity fluctuations per minute for the drivers in the control group than there were for the drivers in the experimental group, the ANOVA revealed that this apparent difference was not statistically significant. However, when a two-tailed sign test was done on the data, it showed that the fact that the number of velocity fluctuations was greater for the control-group drivers than for the experimental-group drivers in nine of nine cases was significant ($p = 0.004$).

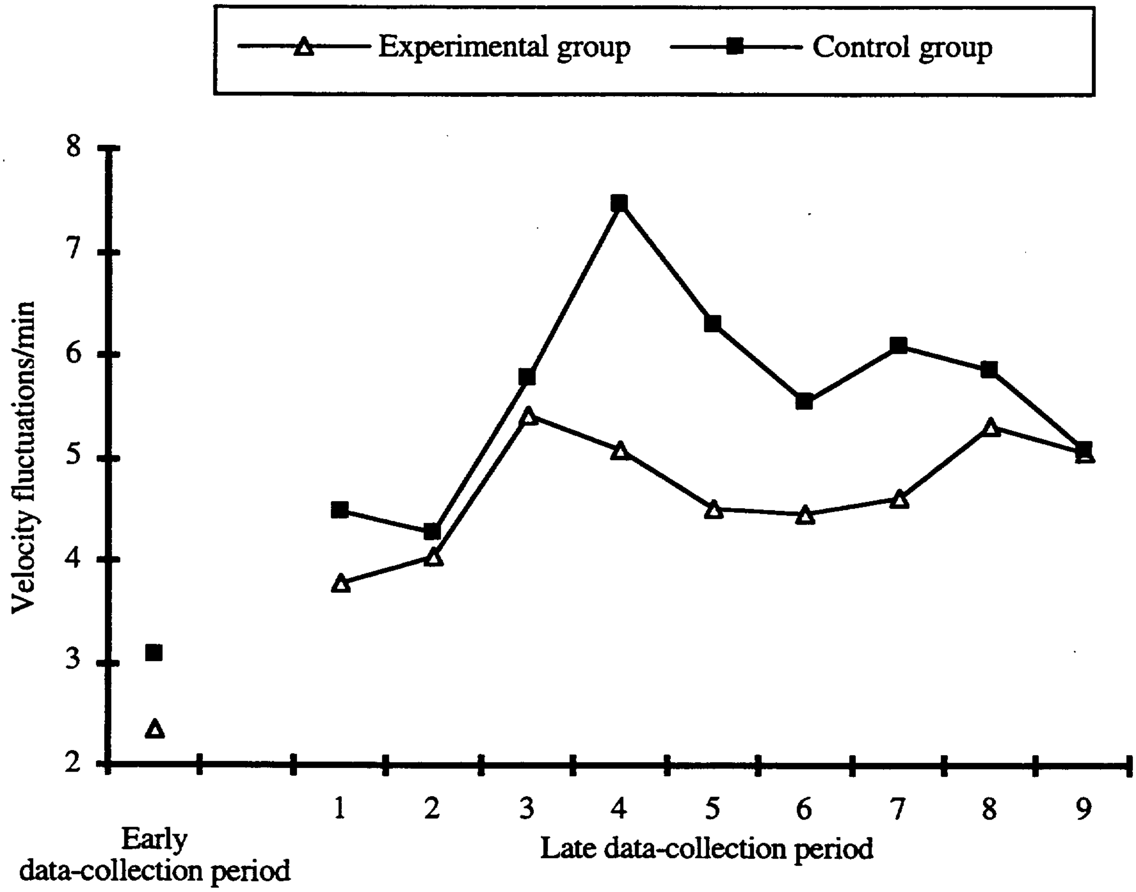

Figure 9. The mean number of velocity fluctuations in the early data-collection period compared with the mean number of velocity fluctuations in each of the nine 1-min segments in the late data-collection period for the drivers in both the control and experimental groups.

MINIMUM FOLLOWING DISTANCE

The minimum following distance data[1] were not segmented like the lane-keeping and speed-control measures. Instead, the minimum following distance for each driver was determined in

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[1] To determine the minimum following distance for each driver, the following procedure was used. First, throughout the two data-collection time periods, the gap between the front bumper of the driver's car and the back bumper of the vehicle ahead was recorded at 30 Hz. Second, if the driver changed lanes, the data obtained during the lane change were eliminated from consideration. Third, whenever the gap between the driver's vehicle and the vehicle ahead exceeded 440 m (1443 ft), the data were eliminated from consideration. Fourth, if after a break in the data the gap increased continuously, the lowest point was ignored (if the gap was continuously increasing, this may have been because the driver was uncomfortable with the gap and had reduced speed to increase it). Fifth, if before a break in the data the gap decreased continuously, the lowest point was also ignored (if the gap was continuously decreasing, this may have been because the gap was still larger than the minimum following distance that was acceptable to the driver). Sixth, the lowest point was selected. Seventh, it was determined whether there were gap data for at least 10 s around the lowest point. If there were less than 10 s of data, they were discarded. Eighth, the gap data

both data-collection periods. The primary question relating to minimum following distance was whether traveling in the automated lane with a much-shorter-than-usual distance between the driver's car and the vehicle immediately ahead would cause the driver to reduce his/her following distance after experiencing travel in the AHS lane. As with the lane-keeping and speed-control measures, the minimum following distance data were analyzed using two ANOVA's, both of which investigated the effects of the data-collection period and the age of the driver. In addition, the first ANOVA investigated the effect of varying the intra-string gap (collapsing the data across the methods of transferring control), while the second ANOVA investigated the effect of varying the method of transferring control back to the driver (collapsing the data across the intra-string gaps). The statistically significant effects found by these two ANOVA's are listed in table 12. The complete summary tables for the both ANOVA's are presented in appendix 7.

Table 12. Summary of the statistically significant effects found in the ANOVA's conducted to determine if the minimum following distance was affected by the data-collection period (D), the age of the driver, the intra-string gap, or the method of transferring control.

	Minimum Following Distance	
Source	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]
D	0.0108	0.0083

[a] Control group is one level of intra-string gap.

[b] Control group is one level of transfer method.

Data-Collection Period. As table 12 shows, both ANOVA's found that the data-collection period had a statistically significant effect on the minimum following distance. The average minimum following distances found in these two periods are shown in figure 10.

Figure 10 shows that there was a reduction in the minimum following distance from the first data-collection period to the second. Since the means shown in the figure were averaged over all the drivers, including the controls, without further information it is not possible to determine whether this effect can be attributed to the driver's exposure to the AHS.

acquired in any period that was 10 s or more were examined. If during this 10-s period the gap exceeded the lowest point by 133 percent, the data were discarded (this is because the lowest point may have occurred because another vehicle moved into the lane ahead of the driver, leaving a gap that was smaller than was acceptable to the driver who, as a result, reduced speed to increase the gap). Ninth, if the data met all the criteria listed above, the lowest point was reported as the minimum following distance for the driver.

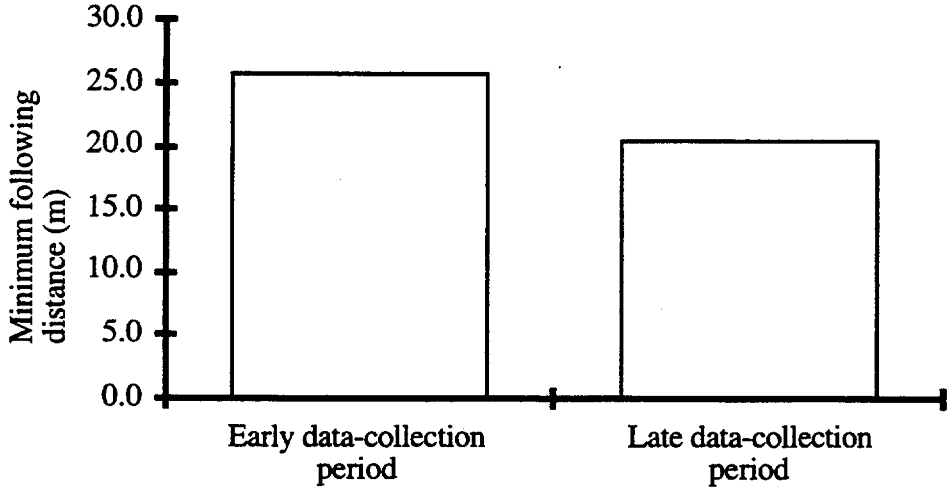

Figure 10. Minimum following distance in the first and second data-collection periods.

LANE-CHANGING BEHAVIOR

The percentage of time spent in the center and right lanes, the number of times the driver changed lanes, and the gaps that the driver moved into when changing lanes are discussed in this section.

Percentage of Time Spent in the Center and Right Lanes

During the early and late data-collection periods, the drivers could drive in the center and right lanes of the expressway: the left lane was reserved for automated vehicles. The total amount of time the drivers spent in the center lane and in the right lane was recorded. Then, these totals were converted into percentages. Since the percentage of time spent in the two lanes is inversely related, it was necessary to conduct ANOVA's on only one of the percentages. Accordingly, two ANOVA's were conducted on the percentage of time spent in the center lane. The first ANOVA determined the effect of varying the intra-string gap on the percentage of time the driver spent in the center lane after traveling under automated control. For this analysis, the data were collapsed over the methods of transferring control. The second ANOVA analyzed the effect of varying the method of transferring control, collapsing the data over the intra-string gaps. The independent variables and interactions that were found to have statistically significant effects are listed in table 13. The complete summary tables for these ANOVA's are presented in appendix 7.

Table 13. Summary of the statistically significant effects found in the ANOVA's conducted to determine if the percentage of time spent in the center lane (and right lane) was affected by the data-collection period (D), the age of the driver (A), the intra-string gap (I), or the method of transferring control (T).

	Percentage of Time in Center Lane	
Source	Intra-String Gap Analysis[a]	Transfer-Method Analysis[b]
I	0.0010	–
A	0.0028	0.0054
D	0.0189	0.0122
T	–	0.0161

[a] Control group is one level of intra-string gap.

[b] Control group is one level of transfer method.

Intra–String Gap. Table 13 indicates that the percentage of time spent in the center lane, and in the right lane, was affected by the intra-string gap. The Tukey Studentized Range test was used to investigate further. It showed that there was no difference in the percentage of time spent in the center (or right) lane by the drivers in the experimental groups, i.e., there were no differences that could be attributed to variations in the size of the intra-string gap. Instead, the difference that was significant was between the drivers in the control group and the drivers in the experimental groups, with the latter spending a greater percentage of time in the center lane than the former.

Data-collection periods. The summaries of the intra-string gap ANOVA and the transfer-method ANOVA, shown in table 13, reveal that there was a statistically significant difference in the percentage of time spent in the center lane (and in the right lane) in the early and late data-collection periods. Figure 11 illustrates this difference.

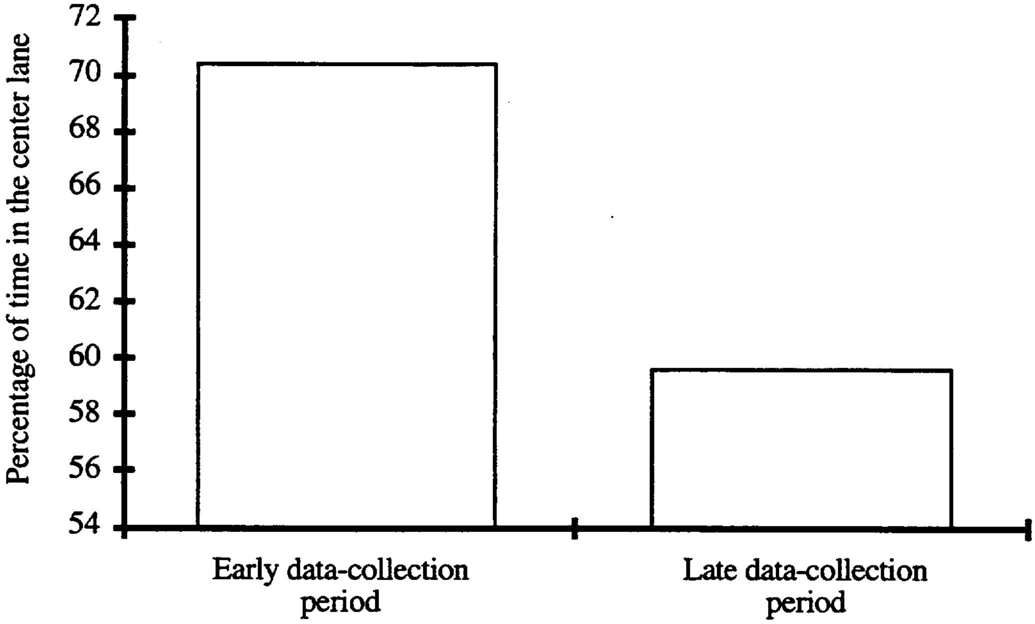

Figure 11. Percentage of time spent in the center lane in the early and late data-collection periods.

Figure 11 shows that, on average, drivers spent 11 percent more time in the center lane (and 11 percent less in the right lane) in the early data-collection period than they did in the late data-collection period. Since the percentages shown in the figure were averaged over all the drivers, including the control group, without further information it is not possible to determine whether this effect can be attributed to traveling in an automated lane.

<u>Age of the Driver.</u> Table 13 indicated that the percentage of time spent by the driver in the center lane (and in the right lane) varied with the age of the driver. Figure 12 shows this variation. The younger drivers drove in the center lane more often (and in the right lane less often) than the older drivers—81 percent and 50 percent of the time, respectively.

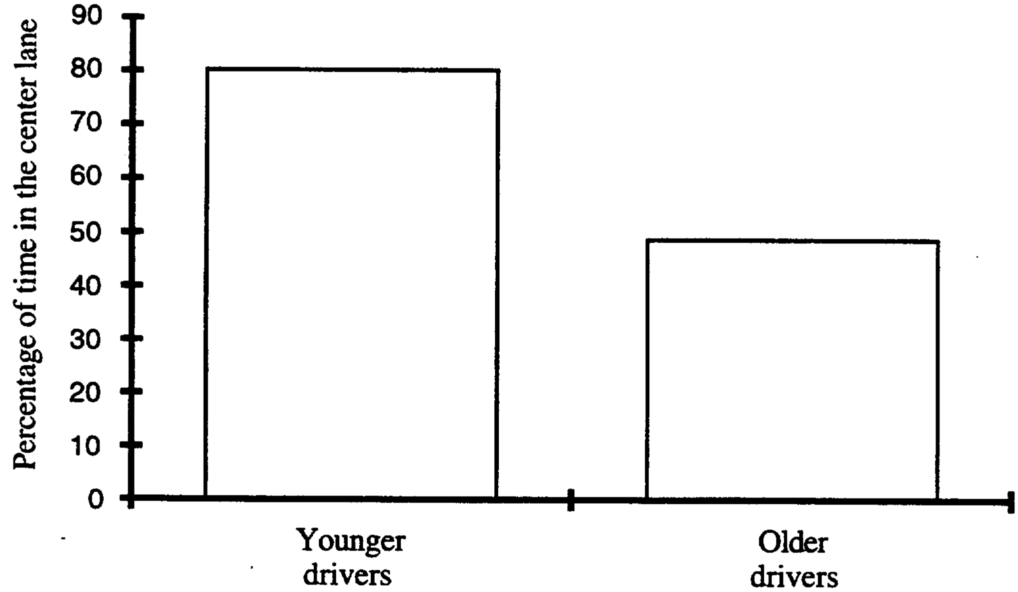

Figure 12. Percentage of time spent in the center lane by younger and older drivers.

Transfer Method. Table 13 indicated a significant effect of method of transferring control to the driver. The data are shown in figure 13. A Tukey Studentized Range test revealed that the difference was between the control group drivers and the experimental group drivers: the drivers in the control group spent less time in the center lane than did the experimental group drivers. Within the experimental group, method of transferring control did not matter.

Number of Lane Changes

As they were driving along the expressway during the two data-collection periods, the drivers were able move between the right and center lanes as they wished. Some drivers did not change lanes in one or both of the data-collection periods. A total of 167 lane changes were recorded in the two data-collection periods. The average numbers of lane changes per driver made in the early and late data-collection periods (before and after automated travel, respectively) are shown in table 14.

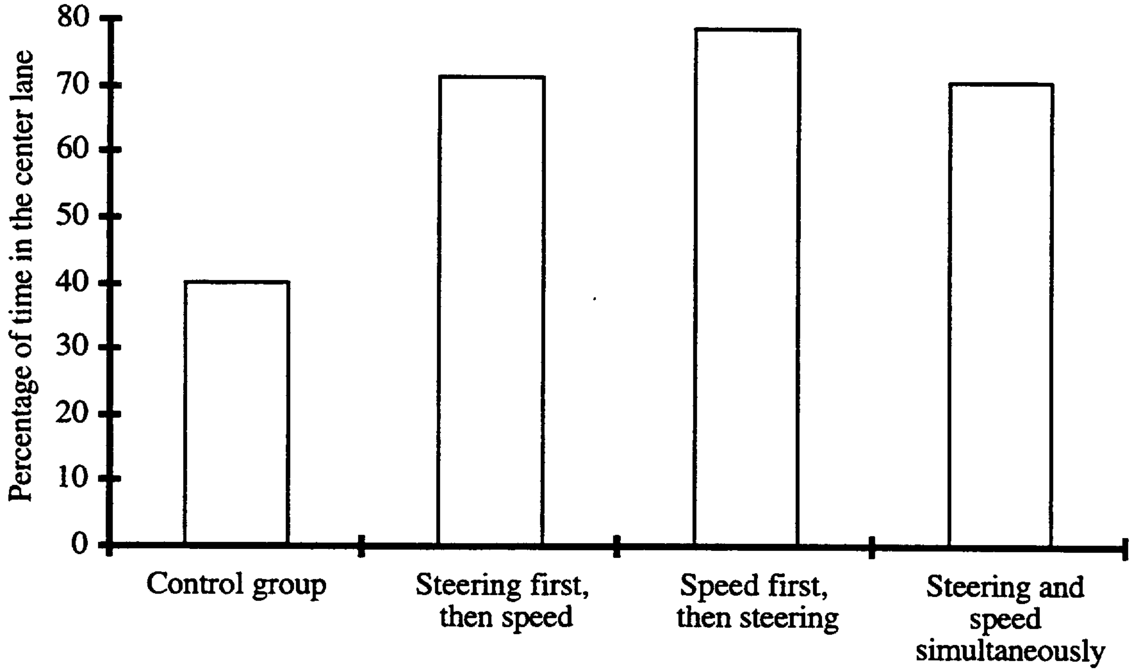

Figure 13. Percentage of time spent in the center lane as a function of control-transfer method.

Table 14. Average number of lane changes (rounded to one decimal place) for younger and older drivers in the control and experimental groups for both data-collection periods.

	Control Group		Experimental Group	
Data-Collection Period	Younger	Older	Younger	Older
Early	1.7	2.7	1.7	1.0
Late	1.2	2.2	2.3	1.8

To determine whether there were any dependencies in the lane-change data, they were regrouped into two 2 by 2 contingency tables for chi-squared analyses. Since the averages were too small to allow that statistic to be run, the total numbers of lane changes were used instead. Tables 15 and 16 show the rearranged data. For group by data-collection period (table 15), the chi-squared test on the data (using the correction for continuity) failed to reach significance ($\chi^2[1] = 3.18$, $p > 0.05$). Thus, group and data-collection period were independent of each other. For group by age (table 16), on the other hand, there was a significant interaction ($\chi^2[1] = 5.47$, $p < 0.02$). The average numbers of lane changes are shown in table 17.

Table 15. Total number of lane changes for each group by data-collection period combination.

Data-collection period	Control Group	Experimental Group
Early	26	48
Late	20	73

Table 16. Total number of lane changes for each group by age combination.

Age Group	Control Group	Experimental Group
Younger	17	71
Older	29	50

Table 17. Average number of lane changes (rounded to one decimal place) for each group by age combination.

Age Group	Control Group	Experimental Group
Younger	2.8	3.9
Older	4.8	2.8

Size of Gap Accepted in Lane Changes

In addition to recording the number of lane changes, the size of the gap that the driver moved into was determined for each lane change that occurred in the early and late data-collection periods. The distance between the back bumper of the vehicle ahead and the front bumper of the vehicle behind in the adjacent lane was recorded. The paucity of data in the various cells of a potential ANOVA made it impossible to do the analysis. For all gaps ≤350 m (1148 ft)—an arbitrary cutoff point equivalent to a 14-s gap for vehicles traveling at the speed limit—the number of lane changes in each 25-m (82-ft) range was divided by the total number of lane changes to get the percentage within that range. Then, cumulative percentages were determined across the entire range of gaps that were plotted. The cumulative percentages of gap sizes accepted in lane

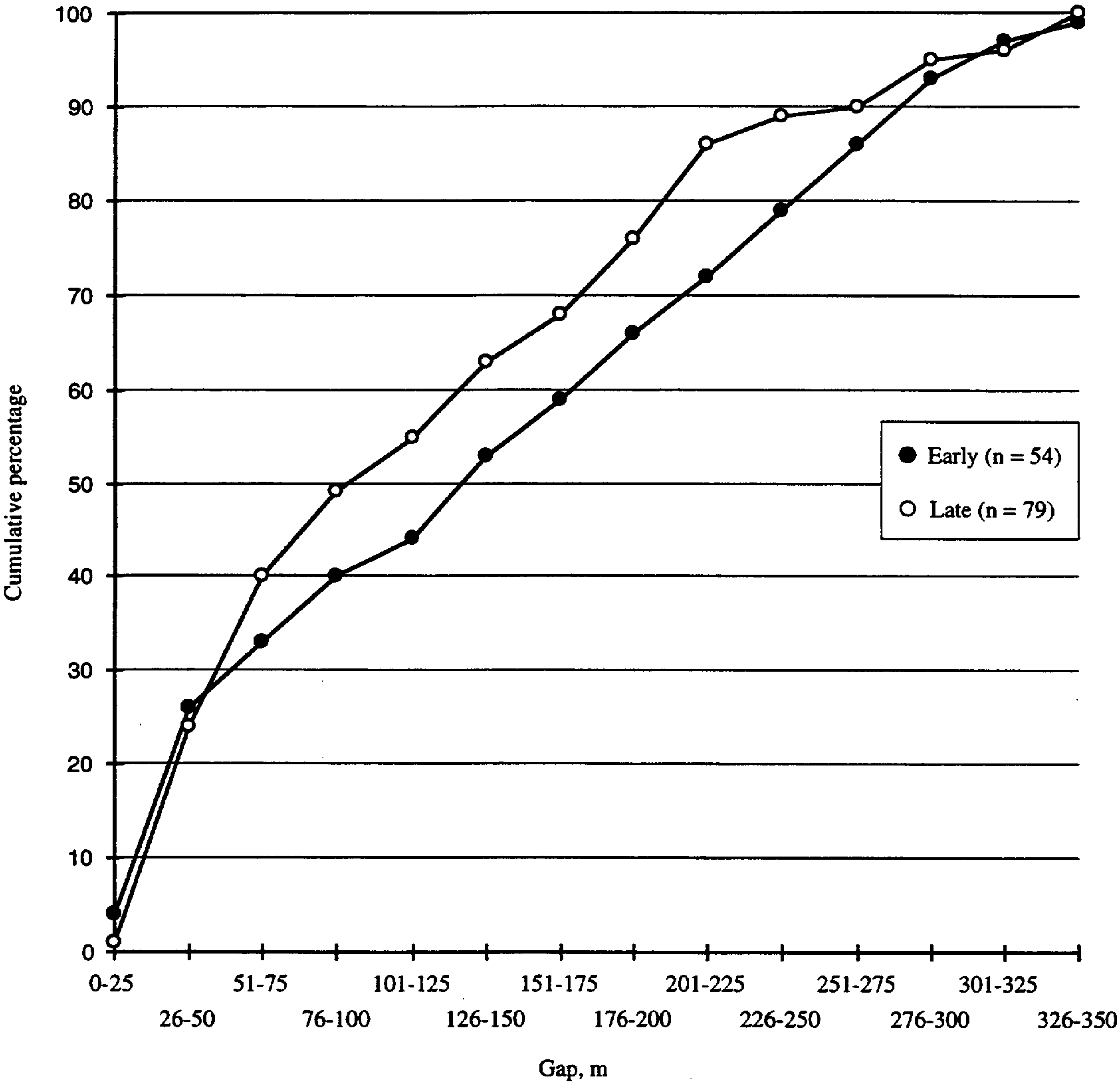

Figure 14. Cumulative percentage of gap size accepted in a lane change. [In the key, n is the number of lane changes plotted. Cumulative percentage may differ from 100 because of rounding error. (1 ft = 1 m x 3.28.)]

changes (subject to the constraint indicated above) are shown in figure 14 for the two data-collection periods, because (by inspection) there did not appear to be any difference between the experimental and control groups, their data were combined. The plots for the early and late data-collection periods are very similar. Based on the raw data (not shown in the report), there is a cluster of gaps between 40 m (131 ft) and 60 m (197 ft) in each data-collection period. Given that drivers drove at about the speed limit (88.6 km/h [55 mi/h]) in both periods, those gaps translate to about 1.6 s and 2.4 s, respectively.

INCURSIONS

Number of Incursions

During the two data-collection periods in this experiment (early and late; before and after automated travel, respectively), there were a number of lane incursions (i.e., occasions when the driver began to change lanes but, for some reason, did not complete the maneuver and instead returned to the lane from which he/she started). There were 140 incursions during the two data-collection periods. Table 18 reports the average number of incursions per driver. To determine whether there were any dependencies in the incursion data, they were regrouped into two 2 by 2 contingency tables for chi-squared analyses. Since the averages were too small to allow that statistic to be run, the total numbers of incursions were used instead. Tables 19 and 20 show the rearranged data. For group by data-collection period (table 19), the chi-squared test on the data (using the correction for continuity) failed to reach significance ($\chi^2[1] = 0.73, p > 0.35$). Thus, group and data-collection period were independent of each other. The test on group by age (table 20), on the other hand, was significant ($\chi^2[1] = 4.22, p < 0.04$), indicating that the number of incursions in each group was dependent on the driver's age. The average numbers of incursions are shown in table 21.

Table 18. Average number of incursions (rounded to one decimal place) for younger and older drivers in the control and experimental groups for both data-collection periods.

	Control Group		Experimental Group	
Data-Collection Period	Younger	Older	Younger	Older
Early	1.3	1.3	1.2	1.8
Late	1.3	0.5	1.0	2.3

Table 19. Total number of incursions for each group by data-collection period combination.

Data-Collection Period	Control Group	Experimental Group
Early	16	54
Late	11	59

Table 20. Total number of incursions for each group by age combination.

Age Group	Control Group	Experimental Group
Younger	16	40
Older	11	73

Table 21. Average number of incursions (rounded to one decimal place) for each group by age combination.

Age Group	Control Group	Experimental Group
Younger	2.7	2.2
Older	1.8	4.1

Size of Gap Rejected When Incursions Occurred

When each incursion occurred, the distance between the back bumper of the vehicle ahead and the front bumper of the vehicle behind in the adjacent lane was recorded. The limited data per cell made an ANOVA impossible. As with the gaps accepted in lane changes, for all incursion gaps that were less than 350 m (1148 ft), the number of incursions in each 25-m (82-ft) range was divided by the total number of incursions to get the percentage within that range. Then, cumulative percentages were determined across the entire range of gaps that were plotted. The cumulative percentages of gap sizes rejected in incursions (subject to the constraint indicated above) are shown in figure 15 for the two data-collection periods. Because (by inspection) there did not appear to be any difference between the experimental and control groups, their data were combined. The plots for the early and late data-collection periods are very similar. Based on the raw data (not shown in the report), there is a cluster of gaps between 40 m (131 ft) and 60 m (197 ft) in each data-collection period, just as there was for gap size accepted in a lane change. Given that drivers drove at about the speed limit (88.6 km/h [55 mi/h]) in both periods, those gaps translate to about 1.6 s and 2.4 s, respectively. It is also noted from the raw data that there were very few gaps shorter than 40 m (131 ft) that were rejected when incursions occurred, suggesting that drivers did not consider moving into gaps that were shorter than this.

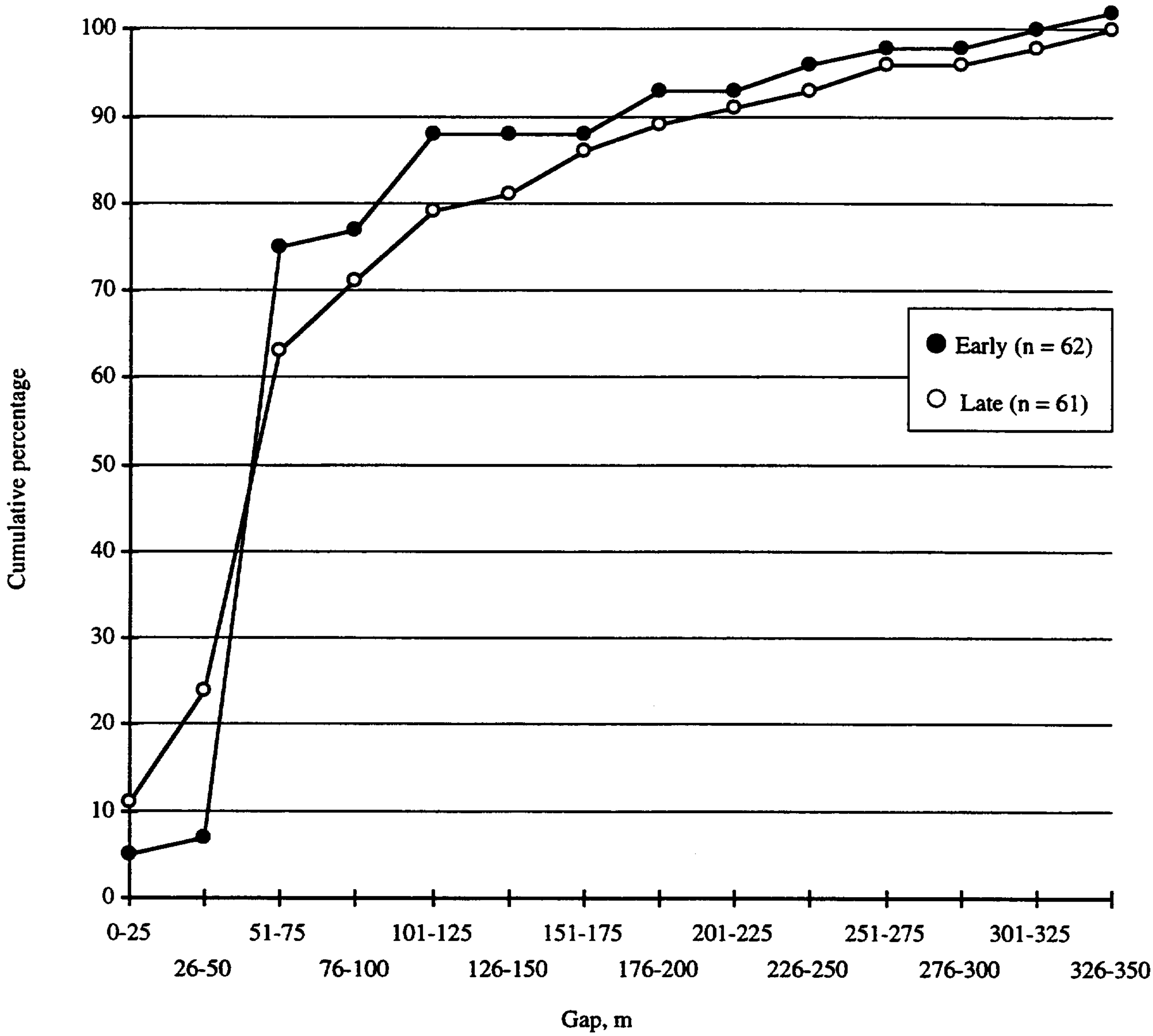

Figure 15. Cumulative percentage of gap size rejected in a lane incursion. [In the key, n is the number of lane changes plotted. Cumulative percentage may differ from 100 because of rounding error. (1 ft = 1 m x 3.28.)]

ACCEPTED VERSUS REJECTED GAPS

Since the shortest gaps accepted in lane changes and the shortest incursion gaps are very similar in length, it is reasonable to ask whether they are related (e.g., do drivers who have the shortest lane-change gaps also have the shortest incursion gaps?). To explore this relationship, the shortest gap into which each driver drove when changing lanes was compared with the shortest gap he/she rejected when there was an incursion. Pairs of values were found for each driver. For the purposes of this comparison, data from the early and late data-collection periods were combined. Then, the correlation between the pairs was tested using Spearman's correlation coefficient.[2] The value of ρ was found to be 0.22, and was not statistically significant. This means that the drivers who had the shortest incursion gaps were not the same drivers who had the shortest lane-change gaps.

QUESTIONNAIRE

Four versions of the questionnaire were used in this experiment: one for each of the three control-transfer methods and one for the control condition. Questions 1 through 6 and 28 through 30 were the same for all conditions. Question 7 was modified so that the drivers in the control group had a slightly different question than those exposed to the AHS. Questions 7 through 25 were administered only to the drivers who traveled in the AHS. Of these items, question 15 was modified to clearly state how the transfer of control from the AHS to driver was made in the particular experimental condition. A copy of each questionnaire is presented in appendix 4.

A scale ranging from 0 to 100 with negatively and positively worded anchors at the ends were provided for each question. Drivers were asked to rate their response as a whole number between 0 and 100. A space was provided next to the question and scale. Dichotomous questions (numbers 9a, 10a, 11a, 12a, 16, and 29) asked the drivers to check a box indicating either yes or no. These items were scored as 0 for no and 1 for yes. Then, a series of ANOVA's was conducted on the data obtained to determine whether age, gender, transfer method, or intra-string gap had affected the responses of the drivers. The results of the analyses of the questions related to the current experiment are presented in the subsections that follow.

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[2] Spearman's ρ was used instead of the Pearson correlation coefficient because both the lane-change gap and the incursion gap data were positively skewed. Only gap data from drivers who changed lanes at least once and made an incursion at some point in either data-collection period could be used in calculating ρ. Some drivers did not change lanes and some did not have an incursion in either data-collection period.

Simulator Realism

The first six questions were presented to gather drivers' opinions on the realism of the Iowa Driving Simulator. No significant differences were found during the ANOVA's. The average response for each question appears in table 22. These means are collapsed across age, gender, transfer method, and intra-string gap.

Table 22. Simulator realism.

Question	Overall Mean
1. How much did you enjoy driving the simulator? 0. Not at all 100. A lot	79.2
2. How did driving in the simulator compare to driving in your car? 0. Very different 100. Very similar	54.9
3. How realistic was the view out of the windshield in the simulator? 0. Very artificial 100. Very realistic	64.5
4. How realistic were the sounds in the simulator? 0. Very artificial 100. Very realistic	66.8
5. How realistic was the vehicle motion in the simulator? 0. Very artificial 100. Very realistic	73.1
6. While driving the simulator, how did you feel? 0. Did not feel well 100. Felt fine	81.0

As can be seen from table 22, all responses averaged above 50, indicating that the drivers had positive attitudes toward the simulator. The responses to three questions were strongly positive, with means above 70—implying that drivers enjoyed driving the simulator (question 1), found the vehicle motion to be realistic (question 5), and felt well while driving the simulator (question 6). Responses to questions 3 and 4 were moderately favorable with means between 60 and 70. These averages indicate that the view out of the windshield and sounds from the simulator were moderately realistic. The average response to the second question was neutral, with a mean of 54.9, indicating that drivers did not feel that driving the simulator was very different from or very similar to driving their own cars.

Designated AHS Velocity and Intra-String Gap

The responses for questions 7 and 8, which dealt with the designated AHS velocity and the intra-string gap, appear in tables 23 and 24.

Table 23. Designated AHS velocity and intra-string gap (question 7).

Question (Control group only)	Overall Mean		
7. In this study, how did you feel about the fact that while you were driving, one of the lanes (the left) was not available for you to use? 0. It didn't matter 100. It mattered a lot	48.5		
Question (Experimental groups only)	Both Steering & Velocity	Steering First then Velocity	Velocity First then Steering
7. In this study, when your car was under automatic control, how did you feel about the speed at which you traveled? 0. Would have preferred to go much slower 100. Would have preferred to go much faster	80.5*	71.3	59.6*

* Indicates these means are significantly different from each other.

Table 24. Designated AHS velocity and intra-string gap (question 8).

Question	Younger	Older
8. In this study, when your car was under automatic control, how did you feel about the separation distance between you and the car ahead? 0. Would have preferred a much longer separation 100. Would have preferred a much shorter separation		
Small Gap	28.9	41.7
Large Gap	42.2	23.8

Question 7 dealt with the use of the automated lane. This question was modified for the control group to focus on how the driver felt about not having access to the left (automated) lane. The question posed to the experimental groups dealt with the drivers' perceptions of the designated AHS velocity. The ANOVA's carried out on these questions showed statistically significant differences for the experimental groups only. As can be seen from table 23, the mean response of the control group indicated that these drivers were neutral about the lack of access to the left (automated) lane. For those traveling in the AHS, a preference for faster velocities in the automated lane was expressed by all groups. The statistically significant difference found for the experimental group indicated that those with the Both Steering and Velocity transfer method would have preferred a much faster speed than those with the Velocity First transfer method. No statistically significant difference was found between the Steering First transfer method and the other two transfer methods.

Question 8 dealt with separation distances in the automated lane. The ANOVA conducted on the responses to this question indicated that there was a statistically significant interaction between the age of the driver and the intra-string gap. Table 24 shows that the younger drivers who experienced the small intra-string gap and the older drivers who experienced the large intra-string gap preferred a longer separation distance than the older drivers with the small intra-string gap and the younger drivers with the large intra-string gap. It is important to note that the means of all groups indicate that a longer separation distance was preferred by all.

Information Display

Questions 9 through 12 dealt with information displays used as part of this experiment. Statistical analyses using ANOVA were conducted on each question. Statistical differences were found for only questions 10b and 12b. Results for all other questions are collapsed across age, gender, transfer method, and intra-string gap. The results are shown in tables 25 and 26.

As can be seen from table 25, the mean responses for the questions where no significant differences were found indicate that the drivers in the experimental groups used the Current Location (question 9a), Next Exit (question 10a), Time to Destination (question 11a), and Traffic Ahead information (question 12a). Mean responses on the usefulness of the Current Location (question 9b) and Time to Destination (question 11b) information indicated that drivers found this information to be useful. While drivers also found the Next Exit information to be useful, there were statistically different responses from the older and younger drivers (question 10b): Older drivers found the Next Exit information to be significantly more useful than did the younger drivers.

Table 25. Information display (questions 9a through 12a).

Question	Overall Mean	
9a. Did you look at the CURRENT LOCATION information during the experiment? 0. No 1. Yes	1.0	
9b. How useful did you find the CURRENT LOCATION information? 0. Not useful 100. Very useful	72.5	
10a. Did you look at the NEXT EXIT information during the experiment? 0. No 1. Yes	1.0	
Question	Younger	Older
10b. How useful did you find the NEXT EXIT information? 0. Not useful 100. Very useful	62.2	85.0
Question	Overall Mean	
11a. Did you look at the TIME TO DESTINATION information during the experiment? 0. No 1. Yes	1.0	
11b. How useful did you find the TIME TO DESTINATION information? 0. Not useful 100. Very useful	82.6	
12a. Did you look at the TRAFFIC AHEAD information during the experiment? 0. No 1. Yes	1.0	

Table 26. Information display (question 12b).

Question		
12b. How useful did you find the TRAFFIC AHEAD information? 0. Not useful 100. Very useful	Younger	Older
Small Gap	78.8	90.8
Large Gap	91.7	58.8

A statistically significant interaction between the age of the driver and the intra-string gap distance was found for question 12b. Older drivers with the small intra-string gap and younger drivers with a large intra-string distance found the traffic ahead information to be more useful than older drivers with a large intra-string gap and younger drivers with a small intra-string gap.

AHS Message

Question 14 dealt with the clarity of the AHS messages presented during this experiment. The ANOVA carried out on this question failed to show any statistical difference in responses. The average response reported in Table 27 is collapsed across age, gender, transfer method, and intra-string gap. Responses to this question indicate that the AHS messages were very easy to understand.

Table 27. AHS message.

Question	Overall Mean
14. How understandable were the messages saying that you should take control of the car? 0. Very hard to understand 100. Very easy to understand	99.7

Transfer of Control from the AHS to the Driver

Questions 15 through 18 dealt with transfer of control from the AHS to the driver. The ANOVA's conducted on these data showed that there were statistically significant differences in the responses for questions 15 and 16 by drivers who experienced the different transfer methods. The results for these two questions are presented in table 28.

The responses to question 15 indicate that drivers who gained control of both the steering and velocity simultaneously rated this transfer method significantly better than those who gained control of velocity first and then steering. There were no statistically significant differences between the ratings of drivers with the steering-first (then velocity) transfer method and drivers in the other two transfer methods. When asked in question 16 if they would have preferred to be given control in some other way, drivers in the velocity-first (then steering) transfer group preferred a different method significantly more than drivers in either the both steering and velocity and the steering-first (then velocity) transfer methods.

Table 28. Transfer of control from AHS to driver (questions 15 and 16).

Question	Both Steering & Velocity	Steering First then Velocity	Velocity First then Steering
15. When you were given back control of the car after the period of automated travel, you took control of (both steering and speed at the same time)/(steering first followed by speed)/(speed first followed by steering). How did you feel about getting control back in this way? 0. This way was very bad 100. This way was very good	97.1*	86.3	77.1*
16. Would you have preferred to have been given control of the car back in some other way? 0. No 1. Yes	0.00[A]	0.00[A]	0.33[B]

* Indicates these means are significantly different from each other.
"A" means are significantly different from "B" means, but not from each other.

The ANOVA for questions 17 and 18 failed to show statistically significant differences. Table 29 shows means for these questions. The means are collapsed across age, gender, transfer method, and intra-string gap. These results indicate that the drivers felt their driving was very controlled immediately after leaving the automated lane (question 17) and that driving at the end was relatively the same as driving at the beginning of the session (question 18).

Table 29. Transfer of control from AHS to driver (questions 17 and 18).

Question	Overall Mean
17. How would you describe the manner in which you controlled your car *immediately after leaving* the automated lane? 0. Very uncontrolled 100. Very controlled	76.9
18. *After leaving the automated lane*, you drove for about 10 minutes. How was your driving at the end of the 10 minutes compared to the beginning? 0. Driving at the end was very different from driving at the beginning 100. Driving at the end was the same as driving at the beginning	66.1

Attitude Toward AHS

Questions 19 through 25 dealt with drivers' attitudes toward the AHS. A statistical analysis was performed on each question. A statistically significant difference was found between younger and older drivers for question 19, indicating that older drivers preferred the automated lanes more than younger drivers. No statistically significant differences were found for questions 20 through 24. Results for these questions are collapsed across age, gender, transfer method, and intra-string gap. Table 30 presents the results for questions 19 through 24. Table 31 gives the responses for question 25.

Table 30. Attitude toward AHS (questions 19 through 24).

Question	Younger	Older
19. Which lane did you prefer to be in? 0. Strongly preferred manual lane 100. Strongly preferred automated lane	63.3	83.9
Question	**Overall Mean**	
20. Which lane was it more challenging to be in? 0. More challenging in the manual lanes 100. More challenging in the automated lane	10.4	
21. How would you feel if an Automated Highway System were installed on I-380 between Iowa City and Waterloo? 0. Very unenthusiastic 100. Very enthusiastic	69.8	
22. If an Automated Highway System were installed on I-380, which lane would you prefer driving in? 0. Would strongly prefer manual lanes 100. Would strongly prefer automated lanes	71.7	
23. If an Automated Highway System were installed on I-380, how would you feel about your safety? 0. Would feel much safer without an Automated Highway System 100. Would feel much safer with an Automated Highway System	66.7	
24. How would the installation of an Automated Highway System affect the stress of driving? 0. Would greatly decrease stress 100. Would greatly increase stress	26.0	

Table 30 indicates that drivers found the manual lanes to be more challenging (question 20), would be enthusiastic about an AHS being installed on a nearby interstate (question 21), would prefer to drive in the automated lanes if this installation were to take place (question 22), would

Table 31. Attitude toward AHS (question 25).

Question	Both Steering & Velocity	Steering First then Velocity	Velocity First then Steering
25. How much would you like to be told as to why the Automated Highway System is doing things with your vehicle such as accelerating, lane changing, and so on? 0. Not at all 100. A lot	72.1	57.1*	89.1*

* Indicates these means are significantly different from each other.

feel safer in an AHS (question 23), and would experience a decrease in stress if an AHS existed (question 24).

Table 31 indicates that the drivers in the velocity-first transfer group would have preferred significantly more information about the things that the vehicle was doing, such as accelerating, lane changing, and so on, than those in the steering-first transfer method group. The drivers in the group where control of the steering and velocity were regained simultaneously did not differ significantly from the other transfer-method groups in their response.

Cruise Control

Questions 29 and 30 dealt with cruise control. Results for these questions are presented in tables 32 and 33. Only the 32 drivers who answered "yes" to question 29 answered question 30.

Table 32. Cruise control (question 29).

Question	Younger	Older
29. Does your vehicle have cruise control? 0. No 1. Yes	0.50	0.92

Small Gap	Large Gap	Controls
0.83	0.78	0.42

Table 33. Cruise control (question 30).

Question	Overall Mean
30. How often do you use the cruise control on your vehicle? 0. Hardly ever 100. Almost always	78.4

The ANOVA conducted on these data indicated that significantly more of the older drivers had cruise control in their vehicles than did the younger drivers. Additionally, significantly more individuals in both the large and small intra-string gap conditions had cruise control in their vehicles than those in the control condition. No interaction effects were found between age and intra-string gap size. Question 30 asked drivers with cruise control how often they use this feature: No significant differences were found. The average for question 30 indicates that those drivers with cruise control use it very frequently.

SECTION 4. DISCUSSION

THE EFFECT ON DRIVING PERFORMANCE OF TRAVELING UNDER AUTOMATED CONTROL

The objectives of this experiment were: (1) to determine whether driving behavior would be affected by traveling for an extended period of time under automated control at a speed greater than the speed limit and with a much-shorter-than-usual distance between the driver's car and the vehicle immediately ahead; (2) to determine the effect on the driver's post-AHS behavior of varying the distance between the driver's car and the vehicle immediately ahead while the driver was traveling in the automated lane; and (3) to determine the effect on the driver's post-AHS behavior of varying the method of transferring control from the AHS back to the driver as his/her vehicle left the automated lane.

Forty-eight drivers participated in this experiment. Thirty-six of these drivers were assigned to the experimental groups, while the remaining 12 were assigned to the control group. There was one experimental trial, lasting approximately 60 min, for each driver. In this trial, the drivers in the experimental group drove the simulator vehicle for the first 15 min of the trial. Then they traveled under automated control for at least 35 min, before controlling the vehicle again for the remaining 10 min of the trial. The drivers in the control group did not travel in the AHS; instead, they stayed in control of the simulator vehicle throughout the trial. Driving-performance data were collected for both groups during two time periods. For both groups of drivers, the early data-collection period, which lasted for 9.5 min, began at the start of the sixth minute of the trial and ended 14.5 min into the trial. For the drivers in the experimental group, the late data-collection period began as soon as control of the vehicle was transferred back to them by the AHS, and ended 9.0 min later. For drivers in the control group, the late data-collection period began at the start of the 52nd minute of the trial and finished at the end of the 60th minute. For analysis purposes, the late data-collection period was divided into nine 1-min segments so that it would be possible to determine the time course of any effects that travel in the AHS had on the driving-performance measures. The data obtained in these 1-min segments were compared with the driving-performance data obtained in the 9.5-min early data-collection period.

Lane-Keeping Performance

The first two driving-performance measures, steering instability and the number of steering oscillations, provided information about the driver's lane-keeping behavior. There was less steering instability for drivers in both the control and experimental groups in the late data-collection period, specifically for the second through ninth minutes of data collection, than there was in the early data-collection period.

Since the reduction in steering instability was found both for drivers in the experimental group and for those in the control group, it is difficult to determine what exactly produced the effect. There could be a common cause: For example, as the trial progressed—whether the driver was in control of the vehicle or the vehicle was being controlled by the AHS—the driver would have become increasingly familiar with the feel of traveling in the simulator vehicle, and this increasing familiarity may have made the driver pay more attention to steering and have led to a reduction in steering instability. Alternatively, there may have been distinct and separate causes for the effect: For example, there may have been a reduction in steering instability for drivers in the experimental group during the late data-collection period because, after their vehicles had been controlled automatically and they had experienced travel in the simulator vehicle with relatively little steering instability, they may have attempted to reproduce this effect by steering as precisely as the AHS. On the other hand, the reduction in steering instability that occurred for the control-group drivers during the late data-collection period may have been the result of those drivers having repeated practice at steering in the earlier parts of the trial. At this point, without further experimentation, it is not possible to determine which of the various explanations is most likely to be correct.

The number of steering oscillations (i.e., the number of times the steering line of best fit was crossed per minute) was unaffected by the period in which the data were collected, the age of the driver, the intra-string gap, or the method of transferring control of the vehicle to the driver.

Speed Control

The next four driving-performance measures all dealt with speed control. The first two variables, average velocity and velocity drift, are considered together. Traveling in the AHS had no effect on either average velocity or velocity drift; there were no statistically significant differences between the early and late data-collection periods for drivers in the control or experimental groups.

Statistically significant differences were found for the other two speed-control measures: average velocity instability and the average number of velocity fluctuations changed from the early to the late data-collection periods. Once again, however, the changes were found for drivers in both the control and experimental groups. The drivers' velocity instability decreased from the early data-collection period to the first 1-min segment of the late data-collection period. It decreased again in the second 1-min segment, and then maintained this lower level throughout the remaining segments in the late data-collection period. There was an increase in the number of velocity fluctuations from the early data-collection period to the first two 1-min segments of the late data-collection period. There was a further increase in the third 1-min segment, after which this higher level was maintained throughout the remainder of the late data-collection period.

As the trial progressed, the drivers appeared to improve their speed control, reducing their velocity instability by making smaller, more frequent adjustments. However, as with the improvement in steering performance mentioned in the previous subsection, since the reduction in velocity instability and the related increase in velocity fluctuations were found both for drivers in the experimental group and for those in the control group, it is difficult to determine what exactly produced these improvements in speed control.

There could have been a common cause: For example, as a result of becoming more familiar with the feel of traveling in the simulator vehicle as the trial progressed, the drivers may have paid more attention to controlling the speed of the vehicle, as well as to steering it, in the late data-collection period. Or, there may have been separate causes of the improvements: For example, improvements may have occurred for drivers in the experimental group during the late data-collection period because, after their vehicles had been controlled automatically, they may have attempted to control the speed and steering of the vehicle as precisely as the AHS. On the other hand, improvements that occurred in the late data-collection period for drivers in the control group may have resulted from their repeated driving practice in the earlier parts of the trial. It might be expected that there would be greater improvements in driving performance for the drivers in the control group—who controlled the vehicle for a longer period of time—than there would be for the drivers in the experimental group—who were being driven by the AHS. There is some evidence to support this expectation: In seven of the nine 1-min segments in the late data-collection period, there was less velocity instability for the drivers in the control group, and in all nine 1-min segments, the average number of velocity fluctuations was greater for the drivers in the control group than for those in the experimental group. However, without more experimentation, this possibility cannot be explored further. [Note: The ANOVA's conducted on velocity instability and on velocity fluctuations (see tables 47 and 48 for the velocity instability ANOVA's and tables 49 and 50 for the velocity fluctuation ANOVA's) did not indicate that there were differences between the experimental groups and the controls. However, recall that the two-tailed sign test showed the statistically significant finding that in nine out of nine cases the mean number of velocity fluctuations was greater for the control-group drivers than it was for the experimental-group drivers.]

Minimum Following Distance

The minimum following distance was less in the late data-collection period compared with the early data-collection period, but there was no difference between the control and experimental groups. Thus, there was no obvious effect of automated travel on minimum following distance.

Time in the Center and Right Lanes

The drivers in the experimental group spent significantly more time in the center lane (and correspondingly less in the right lane) in the early data-collection period than they did in the late data-collection period. They spent 82 percent of the time in the center lane in the early data-collection period and 65 percent there in the late data-collection period. In contrast, the drivers in the control group were in the center lane for 41 percent of the time in the early period, reducing this time only to 40 percent in the late period.

It is probable that the drivers in the experimental groups spent a large percentage of time in the center lane in the early data-collection period because they were aware that they would be instructed to move to the center lane in order to engage the automated system, and they were anticipating this event. Then, they spent less time in the center lane in the late data-collection period because, after traveling under automated control and being deposited in the center lane by the AHS, they moved to the right lane in order to take an exit ramp at the end of their journey.

The reason that the experimental group spent more time in the center lane in the late period than the drivers in the control group, even though they may have been anticipating leaving the expressway, was that they were deposited in the center lane by the AHS.

Lane Changes and Incursions

Traveling under automated control for an extended period of time appears to have had no effect on either the number of lane changes or the size of the gaps accepted by drivers in the experimental groups. Similarly, driving in the simulator for an extended period of time appears to have had no effect on either the number of lane changes or the size of the gaps accepted by drivers in the control group.

However, there was a suggestion that traveling under automated control for an extended period of time may have resulted in some drivers attempting to change lanes into smaller gaps than those into which they attempted to change lanes before traveling under automated control. The smallest of the incursion gaps observed for the drivers who traveled under automated control for an extended period of time appears to have been shorter than the incursion gaps of the drivers in the control group. In the late data-collection period, there were 10 incursion gaps shorter than 40 m (131 ft) for drivers who traveled under automated control, while there were only 2 incursion gaps that were this short for these drivers in the early period. In comparison, for drivers in the control group there was one incursion gap that was shorter than 40 m (131 ft) in each of the data-collection periods.

Intra-String Gap and Method of Transferring Control

The variations in intra-string gap and in the method of transferring control of the vehicle to the driver had no effect on subsequent driving performance. However, there were some responses to the questionnaire that related to the intra-string gap and the method of transferring control. With regard to the intra-string gap, when asked "When your car was under automatic control, how did you feel about the separation distance between you and the car ahead?" drivers responded that they would prefer longer gaps than those they experienced.

As to the method of transferring control, when asked how they felt about the way in which control of the vehicle was given back to them, drivers who were given control of both steering and speed simultaneously gave a significantly stronger positive response than drivers who first got control of the speed, and then subsequently got control of the steering.

OTHER EFFECTS

Age of the Driver

The age of the driver affected two performance measures: the average velocity and the percentage of time spent in the center lane. First, the younger drivers drove significantly faster than the older drivers; the average velocities, over both data-collection periods, were 87.5 km/h (54.3 mi/h) for the younger drivers and 84.2 km/h (52.4 mi/h) for the older drivers. It is to be noted that there is likely no practical significance to this difference. Second, the younger drivers spent more time in the center lane than did older drivers; the percentages were 70 percent and 59 percent, respectively.

Minimum Following Distance

The minimum following distances obtained in this experiment were similar to values obtained by Ohta in a field experiment.[15] The 0.80-s average minimum following distance obtained in the current experiment after the drivers in experimental groups had traveled in the automated lane falls near the center of the 0.6 s to 1.1 s range that Ohta called the "critical range." The average minimum following distances of just over 1.0 s that were obtained for drivers in the experimental group, before they traveled under automated control, and for drivers in the control group in both data-collection periods are close to the upper boundary of this critical range.

Lane Changes and Incursions

The smallest gaps found for both accepted lane-change gaps and the rejected incursion gaps were very similar, between 40 m (131 ft) and 60 m (197 ft), suggesting that the minimum gap acceptable for a lane change is in this region. The drivers were driving at speeds close to the speed limit of 88.6 km/h (55 mi/h) in both the early and late data-collection periods. For a driver traveling at this speed, gaps of 40 m (131 ft) and 60 m (197 ft) are equivalent to gaps of 1.6 s to 2.4 s, respectively.

It should be noted that, although the minimum gaps when the drivers changed lanes and when they made incursions were similar in size, there was no correlation between the size of the gap a particular driver rejected when an incursion occurred and the gap that the same driver accepted when changing lanes.

IMPLICATIONS FOR THE AHS

(1) While it is not clear whether the experience of traveling under automated control produced the reductions in steering instability and velocity instability and the increased number of velocity fluctuations—all of which can be considered as improvements in driving performance—that were found for drivers in the experimental group in the late data-collection period (since similar improvements were found for the drivers in the control group), it is clear that the experience of traveling under automated control did not have an adverse affect on lane keeping and speed control.

(2) Automated travel produced no obvious effect on minimum following distance.

(3) The drivers in the experimental group spent more time in the center lane than drivers in the control group both before and after they traveled under automated control for an extended period of time.

(4) The drivers who traveled under automated control expressed a preference for larger intra-string gaps than those that they experienced in this experiment.

(5) The drivers in the experimental group who were given control of both steering and speed simultaneously gave a significantly stronger positive response when asked how they felt about the method of control transfer than the drivers who first got control of the speed and then subsequently got control of the steering.

APPENDIX 1: MAP OF THE VISUAL DATABASE AND STRIP-MAP GUIDE FOR THE DRIVER

Each participant drove a fixed-time route starting at Exit 7 (County Rd E) heading counterclockwise (see figure 16). Each driver was aware of the upcoming exits via a strip map depicted in figure 17.

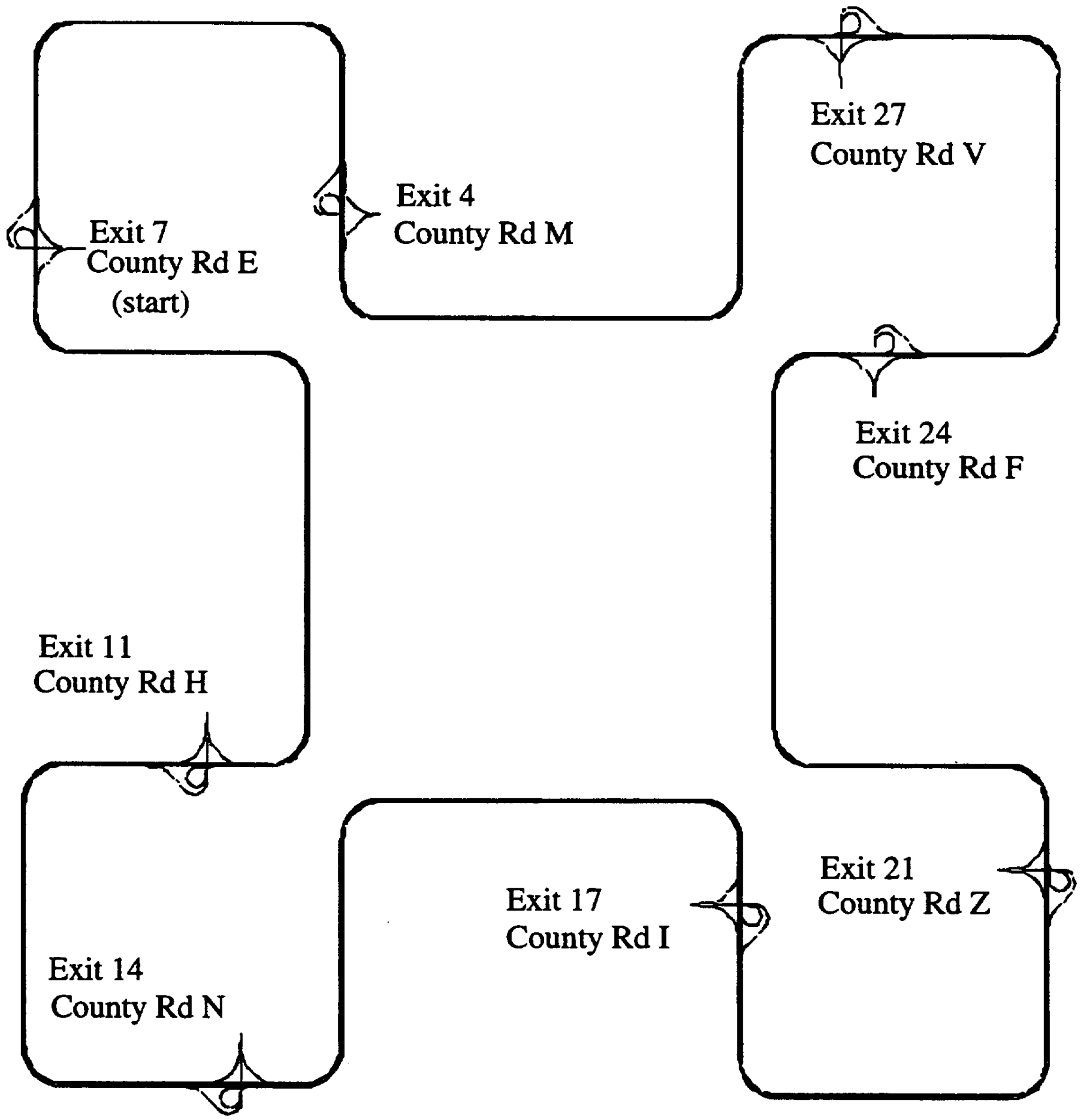

Figure 16. Map of the route driven in experiments 3, 4, and 5.

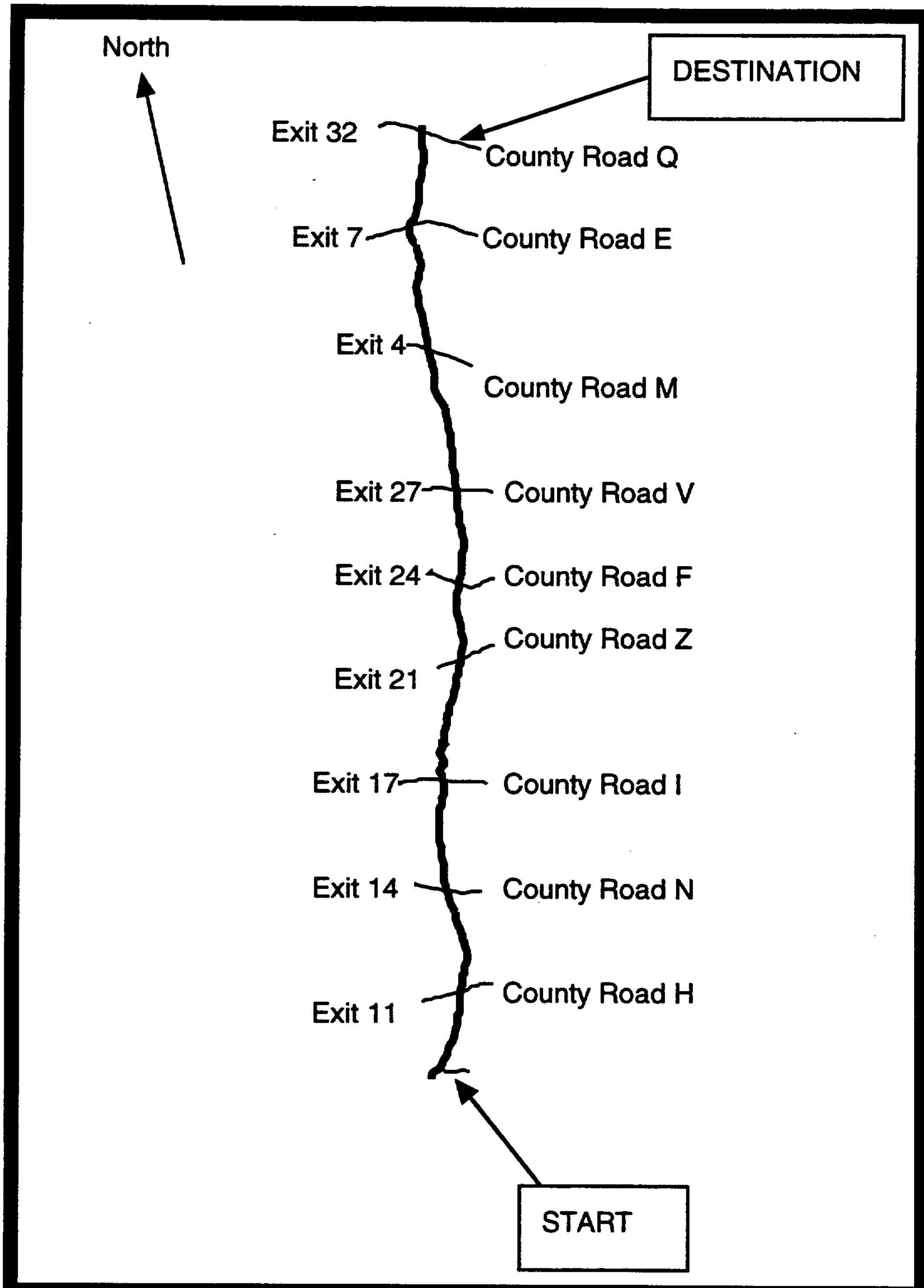

Figure 17. Strip map of the route given to drivers in experiments 3, 4, and 5.

APPENDIX 2: ASSIGNMENT OF DRIVERS TO THE CONDITIONS

The control-transfer method and intra-string gap conditions experienced by each driver were balanced across age and gender. Young males and young females were between 25 and 34 years of age. Older males and older females were age 65 or older. There were three possible transfer-of-control conditions and two possible intra-string gap conditions. There was also a control group, which experienced neither a transfer of control nor an intra-string gap. The way in which the drivers were assigned to these conditions is shown in tables 34 through 37.

Table 34. The transfer condition and gap experienced by younger[1] male drivers.

Driver [2]	Transfer Condition	Intra-String Gap
YM A01	Steering First	0.0344s (1.0m)
YM A02	Velocity First	0.0625s (1.8m)
YM A03	Simultaneous	0.0344s (1.0m)
YM A04	CONTROL	CONTROL
YM A05	Steering First	0.0625s (1.8m)
YM A06	Velocity First	0.0344s (1.0m)
YM A07	Simultaneous	0.0625s (1.8m)
YM A08	CONTROL	CONTROL
YM A09	Steering First	0.0344s (1.0m)
YM A10	Velocity First	0.0625s (1.8m)
YM A11	Simultaneous	0.0344s (1.0m)
YM A12	CONTROL	CONTROL

1 Younger drivers were between 25 and 34 years of age.
2 YM represents the category "younger male."

Table 35. The transfer condition and gap experienced by younger[1] female drivers.

Driver [2]	Transfer Condition	Intra-String Gap
YF A01	CONTROL	CONTROL
YF A02	Simultaneous	0.0625s (1.8m)
YF A03	Velocity First	0.0344s (1.0m)
YF A04	Steering First	0.0625s (1.8m)
YF A05	CONTROL	CONTROL
YF A06	Simultaneous	0.0344s (1.0m)
YF A07	Velocity First	0.0625s (1.8m)
YF A08	Steering First	0.0344s (1.0m)
YF A09	CONTROL	CONTROL
YF A10	Simultaneous	0.0625s (1.8m)
YF A11	Velocity First	0.0344s (1.0m)
YF A12	Steering First	0.0625s (1.8m)

1 Younger drivers were between 25 and 34 years of age.
2 YF represents the category "younger female."

Table 36. The transfer condition and gap experienced by older[1] male drivers.

Driver [2]	Transfer Condition	Intra-String Gap
OM A01	Simultaneous	0.0625s (1.8m)
OM A02	CONTROL	CONTROL
OM A03	Steering First	0.0344s (1.0m)
OM A04	Velocity First	0.0625s (1.8m)
OM A05	Simultaneous	0.0344s (1.0m)
OM A06	CONTROL	CONTROL
OM A07	Steering First	0.0625s (1.8m)
OM A08	Velocity First	0.0344s (1.0m)
OM A09	Simultaneous	0.0625s (1.8m)
OM A10	CONTROL	CONTROL
OM A11	Steering First	0.0344s (1.0m)
OM A12	Velocity First	0.0625s (1.8m)

1 Older drivers were between 65 and 69 years of age (OM A01-OM A06) and age 75 or older (OM A07-OM A12).
2 OM represents the category "older male."

Table 37. The transfer condition and gap experienced by older[1] female drivers.

Driver[2]	Transfer Condition	Intra-String Gap
OF A01	Velocity First	0.0344s (1.0m)
OF A02	Steering First	0.0625s (1.8m)
OF A03	CONTROL	CONTROL
OF A04	Simultaneous	0.0344s (1.0m)
OF A05	Velocity First	0.0625s (1.8m)
OF A06	Steering First	0.0344s (1.0m)
OF A07	CONTROL	CONTROL
OF A08	Simultaneous	0.0625s (1.8m)
OF A09	Velocity First	0.0344s (1.0m)
OF A10	Steering First	0.0625s (1.8m)
OF A11	CONTROL	CONTROL
OF A12	Simultaneous	0.0344s (1.0m)

1 Older drivers were between 65 and 69 years of age (OF A01-OF A06) and age 75 or older (OF A07-OF A12).
2 OF represents the category "older female."

APPENDIX 3: NARRATION FOR THE TRAINING VIDEOS

INTRODUCTION

Each of the 48 drivers who took part in this experiment were assigned to one of four groups. Thirty-six drivers traveled under automated control in the experiment. When these 36 drivers left the automated lane, they used one of three methods of regaining control of their vehicle: the drivers in the first group took control of steering and speed simultaneously; the drivers in the second group first took control of steering, then of speed; and the drivers in the third group first took control of speed then of steering. The remaining 12 drivers did not travel under automated control, but drove their vehicle themselves throughout the experimental trial.

Each driver who took part in this experiment was shown a videotape containing introductory material and experimental instructions. Four different versions of the video were produced, one for each group of drivers. Table 38 shows which video was shown to each of the four groups of drivers.

Table 38. Video shown to each group of drivers.

Video Number	Method of Transferring Control
Video 1.1	Group of drivers who took control of steering and speed simultaneously
Video 1.2	Group of drivers who first took control of steering, then of speed
Video 1.3	Group of drivers who first took control of speed, then of steering
Video 1.4	Group of drivers who did not travel in automated lane

VIDEOTAPE 1.1

The narration for the videotape that was shown to the group of drivers who took control of steering and speed simultaneously was as follows.

[A. Introducing the AHS]

Passage A.1: The study in which you are about to participate is part of an ongoing investigation of Automated Highway Systems. We are conducting the investigation for the FHWA, the Federal Highway Administration. The FHWA is responsible for safety and travel effectiveness on our highways. In this investigation, the FHWA is trying to determine how to design an Automated Highway System in order to reduce congestion and to increase highway safety. We are conducting a series of studies using the Iowa Driving Simulator. We will explore how an Automated Highway System might work, and how well drivers would handle their vehicles in such a system. The data provided by you, and others, will aid us in making accurate and responsible recommendations about how to design and operate the Automated Highway System. This is a test of the Automated Highway System, not a test of you or your driving skills. We will maintain your privacy—your data will never be presented with your name attached.

Passage A.2: The Automated Highway System could be designed in a number of ways. The version that you will drive in the simulator today has been installed on a freeway with three lanes in each direction. In this freeway, the left-most lane is reserved for automated traffic only. All the vehicles in this lane are under the control of the Automated System. They will be arranged in strings—there may be one, two, three, or four vehicles traveling together in each string. The vehicles in the automated lane will be traveling at 65 miles per hour, faster than the traffic in the other two lanes. The right and center lanes are not automated: the vehicles in them will be controlled manually by their drivers.

[B. Driving on the Freeway]

Passage B.1: At the start of the drive, your car will be parked on a freeway entrance ramp. You will drive from the entrance ramp into the right lane. For about 15 minutes, you will drive on the freeway.

Passage B.2: You will be able to drive in the right lane and the center lane, but not in the left lane—that is reserved for automated vehicles. If you start to move into the left lane, you will hear the following warning:
["You've entered the left lane.
You're not authorized to be in the left lane.
Return to the center lane immediately."]

Passage B.3: While you are in the right or center lanes, you will drive among vehicles that are not under automated control—these vehicles will behave in the way that traffic usually behaves on a freeway. The speed limit in the right and center lanes is 55 miles per hour.

[C. Entering the Automated Lane]

Passage C.1: Now, I will describe how you enter the automated lane and join one of the strings of automated vehicles.

Passage C.2: After driving your car for 15 minutes, you will hear a message. If you are in the center lane, the message will be:
["Please remain in the center lane and wait for further instructions."]

Passage C.3: When you hear this message you should remain in the center lane. You will soon hear further instructions.

Passage C.4: If, at the end of the 15 minutes, you are not in the center lane, but are in the right lane instead, you will hear this message:
["Please move to the center lane and, when you get there, wait for further instructions."]

Passage C.5: You should move to the center lane as soon as it is safe to do so.

Passage C.6: After you have been in the center lane a few moments, you will hear the following message:
["To engage the automated system, push the *On* button now."]

Passage C.7: When you push the *On* button, you will hear this message:

["Welcome to the Automated Highway System. Your vehicle is now controlled by the automated system. You will enter the automated lane in a moment."]

Passage C.8: The Automated System will take control. It will keep your car in the center lane, controlling your speed and steering, while it waits for a suitable gap in the automated lane. When it finds a suitable gap between two strings of automated vehicles, the System will move your car into the automated lane. Then, it will increase your speed gradually, until the gap between your car and the string of vehicles ahead narrows and you become the last vehicle in that string.

Passage C.9: Let me review the entry procedure. You will be driving in the right or center lane. If you are in the right lane, you will be asked to move to the center lane—if you are already in the center lane you will be asked to stay there. After a few moments you will be asked to press the *On* button to let the system know that you are ready to enter the automated lane. When you press the *On* button, you will hear a message informing you that the system has taken control of your car. It will move you from the center lane to the automated lane, and increase the speed of your car until you join the string of automated vehicles ahead of you.

[D. Traveling in the Automated Lane]

Passage D.1: For the next 30 minutes, the Automated Highway System will move you along rapidly in the automated lane, steering your car and controlling its speed automatically.

Passage D.2: As you travel along under automated control, the steering wheel will move as the car steers itself. You will notice the steering wheel movement most when the car goes around a curve.

[E. Using the Information Display]

Passage E.1: When you are in the automated lane you will be able to obtain current information about your journey. This information will be presented on the laptop computer that will be mounted to your right in the vehicle. You will be able to obtain information about your current location or the next exit on the freeway; you will be able to learn the time to your destination; and you will be able to obtain information about the state of the traffic ahead.

Passage E.2: You will be able to obtain this information by pressing the keys on a key pad. To discover your current location, you will press 1 on this key pad—you will then be able to see how far you have traveled since the last exit, and how far away you are from the next exit.

Passage E.3: By pressing zero on the key pad you will return to the main menu. Then, if you press 2, you will receive information about the next exit—you will see how far away it is, and how long it will take to get to it while you are traveling in the automated lane.

Passage E.4: To return to the main menu again, you press zero. Now if you press 3, you will receive information about your destination—how far away it is and how long it will take to get to it.

Passage E.5: You press zero to return to the main menu again. Then, by pressing 4 on the key pad, you can obtain information about the state of the traffic ahead.

Passage E.6: You can obtain this information—about your current location, the next exit, your destination, or the state of the traffic—by pressing the appropriate key at any time while you are in the automated lane

Passage E.7: This information will not be available to you before you enter the automated lane or after you leave it and take control of your car again.

[F. Leaving the Automated Lane]

Passage F.1: After you have traveled in the automated lane for about half an hour, you will hear a message informing you that you are about to leave the automated lane. This is what you will hear:
["You will leave the automated lane in 30 seconds. Once in the center lane, you will be asked to resume control of your vehicle."]

Passage F.2: The Automated System will slow your car down to 55 miles an hour. It will continue to control your car as it moves you into the center lane. Then, you will hear the following message:
["To regain control of the vehicle, put your hands on the steering wheel, and press the accelerator or brake pedal."]

Passage F.3: You will not be able to take control of your car until you have heard this message. But when you have heard the message, you should take control as soon as you can. To take control, you must first hold the steering wheel, then press either the accelerator or the brake pedal. When you have done this, the System will transfer control of the car back to you, and you will hear the following message: ["You now have complete control of your vehicle."]

Passage F.4: Once you have complete control of your car, you will be able to drive in the right lane and the center lane, but not in the left lane—that will still be reserved for automated vehicles.

Passage F.5: Let me review the procedure for regaining control of your car. You will hear the message saying you are about to leave the automated lane. The Automated System will reduce the speed of your car, and move it to the center lane. You will hear a second message telling you to take control of your car by holding the steering wheel and pressing the accelerator or the brake pedal. After doing this, you will hear a message confirming that you have control of your car.

Passage F.6: You will then drive in the center and right lanes of the freeway until the end of the drive.

VIDEOTAPE 1.2

The narration for the videotape that was shown to the group of drivers who first took control of steering, then of speed, was as follows.

[A. Introducing the AHS]

Passage A.1: **AS IN VIDEO 1.1**

Passage A.2: **AS IN VIDEO 1.1**

[B. Driving on the Freeway]

Passage B.1: **AS IN VIDEO 1.1**

Passage B.2: **AS IN VIDEO 1.1**

Passage B.3: **AS IN VIDEO 1.1**

[C. Entering the Automated Lane]

Passage C.1: **AS IN VIDEO 1.1**

Passage C.2: **AS IN VIDEO 1.1**

Passage C.3: **AS IN VIDEO 1.1**

Passage C.4: **AS IN VIDEO 1.1**

Passage C.5: **AS IN VIDEO 1.1**

Passage C.6: **AS IN VIDEO 1.1**

Passage C.7: **AS IN VIDEO 1.1**

Passage C.8: **AS IN VIDEO 1.1**

Passage C.9: **AS IN VIDEO 1.1**

[D. Traveling in the Automated Lane]

Passage D.1: **AS IN VIDEO 1.1**

Passage D.2: **AS IN VIDEO 1.1**

[E. Using the Information Display]

Passage E.1: **AS IN VIDEO 1.1**

Passage E.2: **AS IN VIDEO 1.1**

Passage E.3: **AS IN VIDEO 1.1**

Passage E.4: **AS IN VIDEO 1.1**

Passage E.5: **AS IN VIDEO 1.1**

Passage E.6: **AS IN VIDEO 1.1**

Passage E.7: **AS IN VIDEO 1.1**

[F. Leaving the Automated Lane]

Passage F.1: **AS IN VIDEO 1.1**

Passage F.2: **AS IN VIDEO 1.1**

[Note the text in this passage is the same as in video 1.1, but the message that goes with it is different]—

["To regain control of the steering, put your hands on the steering wheel."]

Passage F.3(a): You will not be able to control the steering until you have heard this message. But as soon as you have heard it, you should take control of the steering by putting your hands on the steering wheel.

Passage F.3(b): When you have control of the steering, you will hear the following message:

["You now control the steering. To regain control of the speed, press the accelerator or brake pedal."]

Passage F.3(c): You will not be able to control the speed of your car until you have heard this message. But as soon as you have heard it, you should take control of the speed by pressing either the accelerator or the brake pedal.

Passage F.3(d): When you have pressed the accelerator or the brake pedal, you will hear a message telling you that you now have complete control of your car. This is what you will hear:

["You now have complete control of your vehicle."]

Passage F.4: **AS IN VIDEO 1.1**

Passage F.5: Let me review the procedure for regaining control of your car. You will hear the message saying you are about to leave the automated lane. The Automated System will reduce the speed of your car, and move it to the center lane. Then, you will hear a message telling you to take control of the steering by putting your hands on the steering wheel. When you have control of the steering, you will hear another message—it will tell you to take control of the speed, by pressing the accelerator or brake pedal. After doing this, you will hear a message confirming that you have control of your car.

Passage F.6: **AS IN VIDEO 1.1.**

VIDEOTAPE 1.3

The narration of the videotape that was shown to the group of drivers who first took control of speed, then of the steering, was as follows.

[A. Introducing the AHS]

Passage A.1: **AS IN VIDEO 1.1**

Passage A.2: **AS IN VIDEO 1.1**

[B. Driving on the Freeway]

Passage B.1: **AS IN VIDEO 1.1**

Passage B.2: **AS IN VIDEO 1.1**

Passage B.3: **AS IN VIDEO 1.1**

[C. Entering the Automated Lane]

Passage C.1: **AS IN VIDEO 1.1**

Passage C.2: **AS IN VIDEO 1.1**

Passage C.3: **AS IN VIDEO 1.1**

Passage C.4: **AS IN VIDEO 1.1**

Passage C.5: **AS IN VIDEO 1.1**

Passage C.6: **AS IN VIDEO 1.1**

Passage C.7: **AS IN VIDEO 1.1**

Passage C.8: **AS IN VIDEO 1.1**

Passage C.9: **AS IN VIDEO 1.1**

[D. Traveling in the Automated Lane]

Passage D.1: **AS IN VIDEO 1.1**

Passage D.2: **AS IN VIDEO 1.1**

[E. Using the Information Display]

Passage E.1: **AS IN VIDEO 1.1**

Passage E.2: **AS IN VIDEO 1.1**

Passage E.3: **AS IN VIDEO 1.1**

Passage E.4: **AS IN VIDEO 1.1**

Passage E.5: **AS IN VIDEO 1.1**

Passage E.6: **AS IN VIDEO 1.1**

Passage E.7: **AS IN VIDEO 1.1**

[F. Leaving the Automated Lane]

Passage F.1: **AS IN VIDEO 1.1**

Passage F.2: **AS IN VIDEO 1.1**

> **[Note: the text in this passage is the same as in video 1.1, but the message that goes with it is different]—**
>
> ["To regain control of the speed, press the accelerator or brake pedal."]

Passage F.3(a): You will not be able to control your speed until you have heard this message. But as soon as you have heard it, you should take control of the speed by pressing the accelerator or brake pedal.

Passage F.3(b): When you have control of the speed, you will hear the following message: ["You now control the speed. To regain control of the steering, put your hands on the steering wheel."]

Passage F.3(c): You will not be able to control the steering until you have heard this message. But as soon as you have heard it, you should take control of the steering by putting your hands on the steering wheel.

Passage F.3(d): When you have put your hands on the steering wheel, you will hear a message telling you that you now have complete control of your car. This is what you will hear:
["You now have complete control of your vehicle."]

Passage F.4: **AS IN VIDEO 1.1**

Passage F.5: Let me review the procedure for regaining control of your car. You will hear the message saying you are about to leave the automated lane. The Automated System will reduce the speed of your car, and move it to the center lane. Then, you will hear a message telling you to take control of the speed, by pressing the accelerator or brake pedal. As soon as you have control of the speed, you will hear another message—it will tell you to take control of the steering, by putting your hands on the steering wheel. After doing this, you will hear a message confirming that you have control of your car.

Passage F.6: **AS IN VIDEO 1.1.**

VIDEOTAPE 1.4

The narration of the video that was shown to the drivers who were in the control group (who did not travel in automated lane) was as follows.

[A. Introducing the AHS]

Passage A.1: **[AS IN VIDEO 1.1]**

Passage A.2: The Automated Highway System could be designed in a number of ways. The version you will see today has been installed on a freeway with three lanes in each direction. In this freeway, the left-most lane is reserved for automated traffic only. All the vehicles in this lane are under the control of the Automated System. They will be arranged in strings—there may be one, two, three, or four vehicles traveling together in each string. The vehicles in the automated lane will be traveling at 65 miles per hour, faster than the traffic in the other two lanes. The right and center lanes are not automated: the vehicles in them will be controlled manually by their drivers.

[B. Driving on the Freeway]

Passage B.1: We would like to discover how the drivers who drive only in the manual lanes feel about the left lane being reserved exclusively for automated vehicles. When you drive the simulator today, you will be asked to drive in the right and the center lanes of the freeway only.

Passage B.2: At the start of the drive, your car will be parked on a freeway entrance ramp. You will drive from the entrance ramp into the right lane. You will be able to drive in the right lane and the center lane, but not in the left lane—that is reserved for automated vehicles. If you start to move into the left lane, you will hear the following warning:

["You've entered the left lane.
You're not authorized to be in the left lane.
Return to the center lane immediately."]

Passage B.3: While you are in the right or center lanes, you will drive among vehicles that are not under automated control—these vehicles will behave in the way that traffic usually behaves on a freeway. The speed limit in the right and center lanes is 55 miles per hour.

Passage B.2: **[AS IN VIDEO 1.1]**

Passage B.3: **[AS IN VIDEO 1.1]**

[C. Entering the Automated Lane] OMITTED

[D. Traveling in the Automated Lane] OMITTED

[E. Using the Information Display] OMITTED

[F. Leaving the Automated Lane] OMITTED

APPENDIX 4: QUESTIONNAIRES

The following series of questionnaires dealt with all aspects of the driving simulator, the study that the participants took part in, and the Automated Highway System (as described for experiments 1 through 5). The results of the questions pertaining to experiments 1 and 2 are reported in Levitan and Bloomfield.[7] There is a different questionnaire for each of the control-transfer conditions and a questionnaire for the control condition.

1. Questionnaire for subjects who got control of speed and steering simultaneously.

2. Questionnaire for subjects who got control of steering first.

3. Questionnaire for subjects who got control of speed first.

4. Questionnaire for control subjects.

Questionnaire for Subjects Who Got Control of Speed and Steering Simultaneously

Instructions

The following series of questions deals with the driving simulator, the experiment that you just took part in, and the Automated Highway System. For most of the questions, you will be asked to provide a rating from 0 to 100. The meanings of the two endpoints of the scale are provided for each question. Your answer can be any whole number between 0 and 100; do not use fractions or decimals. A space is provided for you to write your answer in.

Example:

Question	Scale	Your Rating
How would you rate the importance of air bags in driver safety?	0 = Very unimportant 100 = Very important	__________

If you think that air bags are pretty important in driver safety, you would provide a rating of over 50; the more important you think they are, the closer your rating would be to 100. If you think that air bags are not too important, you would provide a rating of less than 50; the more *un*important you think they are, the closer your rating would be to 0.

Questions

Question	Scale	Your Rating
1. How much did you enjoy driving the simulator?	0 = Not at all 100 = A lot	__________
2. How did driving in the simulator compare to driving in your car?	0 = Very different 100 = Very similar	__________
3. How realistic was the view out of the windshield in the simulator?	0 = Very artificial 100 = Very realistic	__________
4. How realistic were the sounds in the simulator?	0 = Very artificial 100 = Very realistic	__________
5. How realistic was the vehicle motion in the simulator?	0 = Very artificial 100 = Very realistic	__________
6. While driving the simulator, how did you feel?	0 = Did not feel well 100 = Felt fine	__________

Question	Scale	Your Rating
7. In this study, when your car was under automatic control, how did you feel about the speed at which you traveled?	0 = Would have preferred to go much slower 100 = Would have preferred to go much faster	________
8. In this study, when your car was under automatic control, how did you feel about the separation distance between you and the car ahead?	0 = Would have preferred a much longer separation 100 = Would have preferred a much shorter separation	________

9–12. During the experiment, when your car was under automated control, you were given an opportunity to request various kinds of information. An example of each kind of information is shown below. For each kind of information, you are asked to tell whether you looked at it during the experiment and to rate its *usefulness*. You are then given an opportunity to tell what you especially liked or did not like about the information presented and how you would change it.

9a. Did you look at the CURRENT LOCATION information (shown below) during the experiment?

- ❑ Yes (Please go to question 9b.)
- ❑ No (Please go to question 10a.)

Question	Scale	Your Rating
9b. How useful did you find the CURRENT LOCATION information?	0 = Not useful 100 = Very useful	________

CURRENT LOCATION

Last exit:	Exit 14, County Road N
Distance past exit:	8.1 miles
Next exit:	Exit 17, County Road I
Distance to exit:	0.3 miles

(Question 9b continued on next page.)

What did you especially like or not like about the CURRENT LOCATION information? How would you change it to make it more *useful*?

____

____

____

____

____

10a. Did you look at the NEXT EXIT information (shown below) during the experiment?
- ❑ Yes (Please go to question 10b.)
- ❑ No (Please go to question 11a.)

Question	Scale	Your Rating
10b. How useful did you find the NEXT EXIT information?	0 = Not useful 100 = Very useful	________

NEXT EXIT

Next exit:	Exit 17, County Road I
Distance to exit:	0.3 miles
Travel time to exit:	0 minutes 18 seconds

What did you especially like or not like about the NEXT EXIT information? How would you change it to make it more *useful*?

____

____

____

____

____

11a. Did you look at the TIME TO DESTINATION information (shown below) during the experiment?
- ☐ Yes (Please go to question 11b.)
- ☐ No (Please go to question 12a.)

Question	Scale	Your Rating
11b. How useful did you find the TIME TO DESTINATION information?	0 = Not useful 100 = Very useful	__________

TIME TO DESTINATION	
Destination:	County Road Q Exit 32
Travel time to destination:	43 minutes 22 seconds

What did you especially like or not like about the TIME TO DESTINATION information? How would you change it to make it more *useful*?

____

____

____

____

____

12a. Did you look at the TRAFFIC AHEAD information (shown on the next page) during the experiment?
- ☐ Yes (Please go to question 12b.)
- ☐ No (Please go to question 13)

Question	Scale	Your Rating
12b. How useful did you find the TRAFFIC AHEAD information?	0 = Not useful 100 = Very useful	____________

TRAFFIC AHEAD	
Distance to destination:	28.4 miles
Traffic ahead:	Accident blocking far right lane at Exit S, 42.7 miles ahead. Traffic congestion in center lane at that exit also.

What did you especially like or not like about the TRAFFIC AHEAD information? How would you change it to make it more *useful*?

____

____

____

____

____

13. Are there other kinds of information you would find useful during an actual trip on an Automated Highway System?

____

____

____

____

____

Question	Scale	Your Rating
14. How understandable were the messages saying that you should take control of your car ("To regain control of the vehicle, put your hands on the steering wheel and press the accelerator or brake")?	0 = Very hard to understand 100 = Very easy to understand	________
15. When you were given back control of the car after the period of automated travel, you took control of both steering and speed at the same time. How did you feel about getting control back in this way?	0 = This way was very bad 100 = This way was very good	________

16. Would you have preferred to have been given control of the car back in some other way?

- ❑ Yes (Please explain below.)
- ❑ No

____

____

____

____

____

Question	Scale	Your Rating
17. How would you describe the manner in which you controlled your car *immediately after leaving* the automated lane?	0 = Very uncontrolled 100 = Very controlled	________

Question	Scale	Your Rating
18. *After leaving the automated lane,* you drove for about 10 minutes. How was your driving at the end of the 10 minutes compared to the beginning?	0 = Driving at the end was very different from driving at the beginning 100 = Driving at the end was the same as driving at the beginning	__________
19. Which lane did you prefer to be in?	0 = Strongly preferred manual lane 100 = Strongly preferred automated lane	__________
20. Which lane was it more challenging to be in?	0 = More challenging in the manual lanes 100 = More challenging in the automated lane	__________
21. How would you feel if an Automated Highway System were installed on I-380 between Iowa City and Waterloo?	0 = Very unenthusiastic 100 = Very enthusiastic	__________
22. If an Automated Highway System were installed on I-380, what lane would you prefer driving in?	0 = Would strongly prefer manual lanes 100 = Would strongly prefer automated lane	__________
23. If an Automated Highway System were installed on I-380, how would you feel about your safety?	0 = Would feel much safer without an Automated Highway System 100 = Would feel much safer with an Automated Highway System	__________
24. How would the installation of an Automated Highway System affect the stress of driving?	0 = Would greatly decrease stress 100 = Would greatly increase stress	__________

Question	Scale	Your Rating
25. How much would you like to be told as to why the Automated Highway System is doing things with your vehicle such as accelerating, lane changing, and so on?	0 = Not at all 100 = A lot	___________

26. What kinds of information would you like to be able to provide *to* the Automated Highway System? (For example, if there is some disturbance on the road ahead, would you like to be able to tell that to the System?)

____

____

____

____

____

27. Do you have any comments on the Automated Highway System?

____

____

____

____

____

28. What type of vehicle do you *usually* drive? Please check one and indicate the make and year.

	Make	Year
❑ Car	___________	______
❑ Van	___________	______
❑ Truck	___________	______
❑ Motorcycle	___________	______
❑ Other (specify) ___________	___________	______

29. Does your vehicle have cruise control?

- ☐ Yes (Please go to question 30.)
- ☐ No (Stop. You have completed the questionnaire.)

Question	Scale	Your Rating
30. How often do you use the cruise control on your vehicle?	0 = Hardly ever 100 = Almost always	________

Questionnaire for Subjects Who Got Control of Steering First

Instructions

The following series of questions deals with the driving simulator, the experiment that you just took part in, and the Automated Highway System. For most of the questions, you will be asked to provide a rating from 0 to 100. The meanings of the two endpoints of the scale are provided for each question. Your answer can be any whole number between 0 and 100; do not use fractions or decimals. A space is provided for you to write your answer in.

Example:

Question	Scale	Your Rating
How would you rate the importance of air bags in driver safety?	0 = Very unimportant 100 = Very important	________

If you think that air bags are pretty important in driver safety, you would provide a rating of over 50; the more important you think they are, the closer your rating would be to 100. If you think that air bags are not too important, you would provide a rating of less than 50; the more *un*important you think they are, the closer your rating would be to 0.

Questions

Question	Scale	Your Rating
1. How much did you enjoy driving the simulator?	0 = Not at all 100 = A lot	________
2. How did driving in the simulator compare to driving in your car?	0 = Very different 100 = Very similar	________
3. How realistic was the view out of the windshield in the simulator?	0 = Very artificial 100 = Very realistic	________
4. How realistic were the sounds in the simulator?	0 = Very artificial 100 = Very realistic	________
5. How realistic was the vehicle motion in the simulator?	0 = Very artificial 100 = Very realistic	________
6. While driving the simulator, how did you feel?	0 = Did not feel well 100 = Felt fine	________

Question	Scale	Your Rating
7. In this study, when your car was under automatic control, how did you feel about the speed at which you traveled?	0 = Would have preferred to go much slower 100 = Would have preferred to go much faster	________
8. In this study, when your car was under automatic control, how did you feel about the separation distance between you and the car ahead?	0 = Would have preferred a much longer separation 100 = Would have preferred a much shorter separation	________

9–12. During the experiment, when your car was under automated control, you were given an opportunity to request various kinds of information. An example of each kind of information is shown below. For each kind of information, you are asked to tell whether you looked at it during the experiment and to rate its *usefulness*. You are then given an opportunity to tell what you especially liked or did not like about the information presented and how you would change it.

9a. Did you look at the CURRENT LOCATION information (shown below) during the experiment?

- ☐ Yes (Please go to question 9b.)
- ☐ No (Please go to question 10a.)

Question	Scale	Your Rating
9b. How useful did you find the CURRENT LOCATION information?	0 = Not useful 100 = Very useful	________

CURRENT LOCATION	
Last exit:	Exit 14, County Road N
Distance past exit:	8.1 miles
Next exit:	Exit 17, County Road I
Distance to exit:	0.3 miles

(Question 9b continued on next page.)

What did you especially like or not like about the CURRENT LOCATION information? How would you change it to make it more *useful*?

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10a. Did you look at the NEXT EXIT information (shown below) during the experiment?

- ❑ Yes (Please go to question 10b.)
- ❑ No (Please go to question 11a.)

Question	Scale	Your Rating
10b. How useful did you find the NEXT EXIT information?	0 = Not useful 100 = Very useful	________

NEXT EXIT	
Next exit:	Exit 17, County Road I
Distance to exit:	0.3 miles
Travel time to exit:	0 minutes 18 seconds

What did you especially like or not like about the NEXT EXIT information? How would you change it to make it more *useful*?

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11a. Did you look at the TIME TO DESTINATION information (shown below) during the experiment?
- ❑ Yes (Please go to question 11b.)
- ❑ No (Please go to question 12a.)

Question	Scale	Your Rating
11b. How useful did you find the TIME TO DESTINATION information?	0 = Not useful 100 = Very useful	________

TIME TO DESTINATION	
Destination:	County Road Q Exit 32
Travel time to destination:	43 minutes 22 seconds

What did you especially like or not like about the TIME TO DESTINATION information? How would you change it to make it more *useful*?

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12a. Did you look at the TRAFFIC AHEAD information (shown on the next page) during the experiment?
- ❑ Yes (Please go to question 12b.)
- ❑ No (Please go to question 13)

Question	Scale	Your Rating
12b. How useful did you find the TRAFFIC AHEAD information?	0 = Not useful 100 = Very useful	______

TRAFFIC AHEAD	
Distance to destination:	28.4 miles
Traffic ahead:	Accident blocking far right lane at Exit S, 42.7 miles ahead. Traffic congestion in center lane at that exit also.

What did you especially like or not like about the TRAFFIC AHEAD information? How would you change it to make it more *useful*?

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13. Are there other kinds of information you would find useful during an actual trip on an Automated Highway System?

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Question	Scale	Your Rating
14. How understandable were the messages saying that you should take control of your car ("To regain control of the steering, put your hands on the steering wheel" and "You now control the steering. To regain control of the speed, press the accelerator or brake pedal")?	0 = Very hard to understand 100 = Very easy to understand	________
15. When you were given back control of the car after the period of automated travel, you took control of steering first followed by speed. How did you feel about getting control back in this way?	0 = This way was very bad 100 = This way was very good	________

16. Would you have preferred to have been given control of the car back in some other way?

❑ Yes (Please explain below.)

❑ No

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Question	Scale	Your Rating
17. How would you describe the manner in which you controlled your car *immediately after leaving* the automated lane?	0 = Very uncontrolled 100 = Very controlled	________

Question	Scale	Your Rating
18. *After leaving the automated lane,* you drove for about 10 minutes. How was your driving at the end of the 10 minutes compared to the beginning?	0 = Driving at the end was very different from driving at the beginning 100 = Driving at the end was the same as driving at the beginning	________
19. Which lane did you prefer to be in?	0 = Strongly preferred manual lane 100 = Strongly preferred automated lane	________
20. Which lane was it more challenging to be in?	0 = More challenging in the manual lanes 100 = More challenging in the automated lane	________
21. How would you feel if an Automated Highway System were installed on I-380 between Iowa City and Waterloo?	0 = Very unenthusiastic 100 = Very enthusiastic	________
22. If an Automated Highway System were installed on I-380, what lane would you prefer driving in?	0 = Would strongly prefer manual lanes 100 = Would strongly prefer automated lane	________
23. If an Automated Highway System were installed on I-380, how would you feel about your safety?	0 = Would feel much safer without an Automated Highway System 100 = Would feel much safer with an Automated Highway System	________
24. How would the installation of an Automated Highway System affect the stress of driving?	0 = Would greatly decrease stress 100 = Would greatly increase stress	________

Question	Scale	Your Rating
25. How much would you like to be told as to why the Automated Highway System is doing things with your vehicle such as accelerating, lane changing, and so on?	0 = Not at all 100 = A lot	________

26. What kinds of information would you like to be able to provide *to* the Automated Highway System? (For example, if there is some disturbance on the road ahead, would you like to be able to tell that to the System?)

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27. Do you have any comments on the Automated Highway System?

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28. What type of vehicle do you *usually* drive? Please check one and indicate the make and year.

	Make	Year
❑ Car	________	_____
❑ Van	________	_____
❑ Truck	________	_____
❑ Motorcycle	________	_____
❑ Other (specify) ________	________	_____

29. Does your vehicle have cruise control?

- ☐ Yes (Please go to question 30.)
- ☐ No (Stop. You have completed the questionnaire.)

Question	Scale	Your Rating
30. How often do you use the cruise control on your vehicle?	0 = Hardly ever 100 = Almost always	________

Questionnaire for Subjects Who Got Control of Speed First

Instructions

The following series of questions deals with the driving simulator, the experiment that you just took part in, and the Automated Highway System. For most of the questions, you will be asked to provide a rating from 0 to 100. The meanings of the two endpoints of the scale are provided for each question. Your answer can be any whole number between 0 and 100; do not use fractions or decimals. A space is provided for you to write your answer in.

Example:

Question	Scale	Your Rating
How would you rate the importance of air bags in driver safety?	0 = Very unimportant 100 = Very important	__________

If you think that air bags are pretty important in driver safety, you would provide a rating of over 50; the more important you think they are, the closer your rating would be to 100. If you think that air bags are not too important, you would provide a rating of less than 50; the more *un*important you think they are, the closer your rating would be to 0.

Questions

Question	Scale	Your Rating
1. How much did you enjoy driving the simulator?	0 = Not at all 100 = A lot	__________
2. How did driving in the simulator compare to driving in your car?	0 = Very different 100 = Very similar	__________
3. How realistic was the view out of the windshield in the simulator?	0 = Very artificial 100 = Very realistic	__________
4. How realistic were the sounds in the simulator?	0 = Very artificial 100 = Very realistic	__________
5. How realistic was the vehicle motion in the simulator?	0 = Very artificial 100 = Very realistic	__________
6. While driving the simulator, how did you feel?	0 = Did not feel well 100 = Felt fine	__________

Question	Scale	Your Rating
7. In this study, when your car was under automatic control, how did you feel about the speed at which you traveled?	0 = Would have preferred to go much slower 100 = Would have preferred to go much faster	________
8. In this study, when your car was under automatic control, how did you feel about the separation distance between you and the car ahead?	0 = Would have preferred a much longer separation 100 = Would have preferred a much shorter separation	________

9–12. During the experiment, when your car was under automated control, you were given an opportunity to request various kinds of information. An example of each kind of information is shown below. For each kind of information, you are asked to tell whether you looked at it during the experiment and to rate its *usefulness*. You are then given an opportunity to tell what you especially liked or did not like about the information presented and how you would change it.

9a. Did you look at the CURRENT LOCATION information (shown below) during the experiment?

- ☐ Yes (Please go to question 9b.)
- ☐ No (Please go to question 10a.)

Question	Scale	Your Rating
9b. How useful did you find the CURRENT LOCATION information?	0 = Not useful 100 = Very useful	________

CURRENT LOCATION

Last exit:	Exit 14, County Road N
Distance past exit:	8.1 miles
Next exit:	Exit 17, County Road I
Distance to exit:	0.3 miles

(Question 9b continued on next page.)

What did you especially like or not like about the CURRENT LOCATION information? How would you change it to make it more *useful*?

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10a. Did you look at the NEXT EXIT information (shown below) during the experiment?
- ❑ Yes (Please go to question 10b.)
- ❑ No (Please go to question 11a.)

Question	Scale	Your Rating
10b. How useful did you find the NEXT EXIT information?	0 = Not useful 100 = Very useful	__________

NEXT EXIT	
Next exit:	Exit 17, County Road I
Distance to exit:	0.3 miles
Travel time to exit:	0 minutes 18 seconds

What did you especially like or not like about the NEXT EXIT information? How would you change it to make it more *useful*?

____

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____

11a. Did you look at the TIME TO DESTINATION information (shown below) during the experiment?
- ❑ Yes (Please go to question 11b.)
- ❑ No (Please go to question 12a.)

Question	Scale	Your Rating
11b. How useful did you find the TIME TO DESTINATION information?	0 = Not useful 100 = Very useful	________

TIME TO DESTINATION	
Destination:	County Road Q Exit 32
Travel time to destination:	43 minutes 22 seconds

What did you especially like or not like about the TIME TO DESTINATION information? How would you change it to make it more *useful*?

____

____

____

____

____

12a. Did you look at the TRAFFIC AHEAD information (shown on the next page) during the experiment?
- ❑ Yes (Please go to question 12b.)
- ❑ No (Please go to question 13)

Question	Scale	Your Rating
12b. How useful did you find the TRAFFIC AHEAD information?	0 = Not useful 100 = Very useful	______

TRAFFIC AHEAD	
Distance to destination:	28.4 miles
Traffic ahead:	Accident blocking far right lane at Exit S, 42.7 miles ahead. Traffic congestion in center lane at that exit also.

What did you especially like or not like about the TRAFFIC AHEAD information? How would you change it to make it more *useful*?

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13. Are there other kinds of information you would find useful during an actual trip on an Automated Highway System?

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Question	Scale	Your Rating
14. How understandable were the messages saying that you should take control of your car ("To regain control of the speed, press the accelerator or brake pedal" and "You now control the speed. To regain control of the steering, put your hands on the steering wheel")?	0 = Very hard to understand 100 = Very easy to understand	________
15. When you were given back control of the car after the period of automated travel, you took control of speed first followed by steering. How did you feel about getting control back in this way?	0 = This way was very bad 100 = This way was very good	________

16. Would you have preferred to have been given control of the car back in some other way?

- ❑ Yes (Please explain below.)
- ❑ No

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Question	Scale	Your Rating
17. How would you describe the manner in which you controlled your car *immediately after leaving* the automated lane?	0 = Very uncontrolled 100 = Very controlled	________

Question	Scale	Your Rating
18. *After leaving the automated lane,* you drove for about 10 minutes. How was your driving at the end of the 10 minutes compared to the beginning?	0 = Driving at the end was very different from driving at the beginning 100 = Driving at the end was the same as driving at the beginning	________
19. Which lane did you prefer to be in?	0 = Strongly preferred manual lane 100 = Strongly preferred automated lane	________
20. Which lane was it more challenging to be in?	0 = More challenging in the manual lanes 100 = More challenging in the automated lane	________
21. How would you feel if an Automated Highway System were installed on I-380 between Iowa City and Waterloo?	0 = Very unenthusiastic 100 = Very enthusiastic	________
22. If an Automated Highway System were installed on I-380, what lane would you prefer driving in?	0 = Would strongly prefer manual lanes 100 = Would strongly prefer automated lane	________
23. If an Automated Highway System were installed on I-380, how would you feel about your safety?	0 = Would feel much safer without an Automated Highway System 100 = Would feel much safer with an Automated Highway System	________
24. How would the installation of an Automated Highway System affect the stress of driving?	0 = Would greatly decrease stress 100 = Would greatly increase stress	________

Question	Scale	Your Rating
25. How much would you like to be told as to why the Automated Highway System is doing things with your vehicle such as accelerating, lane changing, and so on?	0 = Not at all 100 = A lot	________

26. What kinds of information would you like to be able to provide *to* the Automated Highway System? (For example, if there is some disturbance on the road ahead, would you like to be able to tell that to the System?)

____

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27. Do you have any comments on the Automated Highway System?

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28. What type of vehicle do you *usually* drive? Please check one and indicate the make and year.

	Make	Year
❑ Car	________	______
❑ Van	________	______
❑ Truck	________	______
❑ Motorcycle	________	______
❑ Other (specify) ________	________	______

29. Does your vehicle have cruise control?

- ❑ Yes (Please go to question 30.)
- ❑ No (Stop. You have completed the questionnaire.)

Question	Scale	Your Rating
30. How often do you use the cruise control on your vehicle?	0 = Hardly ever 100 = Almost always	________

Questionnaire for Control Subjects

Instructions

The following series of questions deals with the driving simulator, the experiment that you just took part in, and the Automated Highway System. For most of the questions, you will be asked to provide a rating from 0 to 100. The meanings of the two endpoints of the scale are provided for each question. Your answer can be any whole number between 0 and 100; do not use fractions or decimals. A space is provided for you to write your answer in.

Example:

Question	Scale	Your Rating
How would you rate the importance of air bags in driver safety?	0 = Very unimportant 100 = Very important	________

If you think that air bags are pretty important in driver safety, you would provide a rating of over 50; the more important you think they are, the closer your rating would be to 100. If you think that air bags are not too important, you would provide a rating of less than 50; the more *un*important you think they are, the closer your rating would be to 0.

Questions

Question	Scale	Your Rating
1. How much did you enjoy driving the simulator?	0 = Not at all 100 = A lot	________
2. How did driving in the simulator compare to driving in your car?	0 = Very different 100 = Very similar	________
3. How realistic was the view out of the windshield in the simulator?	0 = Very artificial 100 = Very realistic	________
4. How realistic were the sounds in the simulator?	0 = Very artificial 100 = Very realistic	________
5. How realistic was the vehicle motion in the simulator?	0 = Very artificial 100 = Very realistic	________
6. While driving the simulator, how did you feel?	0 = Did not feel well 100 = Felt fine	________

Question	Scale	Your Rating
7. In this study, how did you feel about the fact that while you were driving, one of the lanes (the left) was not available for you to use?	0 = It didn't matter 100 = It mattered a lot	________

8. What type of vehicle do you *usually* drive? Please check one and indicate the make and year.

	Make	Year
❑ Car	________	______
❑ Van	________	______
❑ Truck	________	______
❑ Motorcycle	________	______
❑ Other (specify) ________	________	______

9. Does your vehicle have cruise control?

❑ Yes (Please go to question 10.)

❑ No (Stop. You have completed the questionnaire.)

Question	Scale	Your Rating
10. How often do you use the cruise control on your vehicle?	0 = Hardly ever 100 = Almost always	________

APPENDIX 5: DRIVING MEASURES

Using ideas derived from regression analysis, Bloomfield and Carroll developed a set of lane-keeping and speed-control measures.(14) They showed how to determine two linear equations. The first of these is a lane-keeping equation that represents the line of best fit for a series of points that indicate the offset of the center of a vehicle from the center of the lane, as the vehicle travels along the freeway. The second is a speed-control equation that represents the line of best fit for a second series of points that indicate the velocity of vehicle, as it travels along the freeway.

The lane-keeping equation describes the position of the vehicle relative to the center of the lane at a given time. It indicates how far the vehicle is offset to the left, or right, of the center line of the lane. It also shows whether the vehicle is veering to the left or to the right or is traveling parallel to the lane throughout the series of points. The variability of the actual track of the vehicle around this line of best fit is used, along with the number of crossings of the direction of travel (or line of best fit), to indicate the stability of the driver in maintaining the track of the vehicle. In the current experiment, data were collected at a rate of 30 Hz, so that, as the vehicle traveled along a straight road segment, the track of the vehicle could be used to determine the position of the center of the vehicle relative to a series of perpendicular lines drawn at 1/30-s intervals.

Bloomfield and Carroll assume that the series of positions can be described by the following linear equation:

$$p = a_{lk} - b_{lk}x \tag{1}$$

where:

- p is the point (representing the center of the driver's vehicle) at which the line of best fit crosses the perpendicular across the lane after the vehicle has traveled distance x.
- x is the distance traveled in the lane by the vehicle.
- a_{lk} is the point at which the line of best fit crosses the perpendicular at the start of the straight road segment.
- b_{lk} is the gradient of the line of best fit—it is essentially the steering drift.

The series of positions of the center of the vehicle is unlikely to fall exactly on a straight line. However, since in comparison to the 3.66-m (12-ft) width of the lane, the vehicle will travel along what is, relatively speaking, a very long, straight road segment, it is not unreasonable to assume that the series of positions can be described by a linear equation. Because the equation suggested by Bloomfield and Carroll is a linear regression equation, the line of best fit of this equation can be calculated using the method of least squares. Using the method of least squares, which minimizes the error in predicting p from x, the terms a_{lk} and b_{lk} are calculated as follows:

$$b_{lk} = \frac{\sum xp - \frac{(\sum x)(\sum p)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \qquad (2)$$

where n is the number of data points obtained while the vehicle travels distance x, and

$$a_{lk} = \frac{1}{n}\left(\sum p - b_{lk} \sum x\right) \qquad (3)$$

In addition, the variability in b_{lk}—the residual standard deviation—can be used as an estimate of I_{lk}, the steering instability. I_{lk} provides an estimate of the variability in steering that occurs when the driver is attempting to maintain a straight course along the line of best fit. It is given by the equation:

$$I_{lk} = \sqrt{\left[\sum p^2 - \frac{(\sum p)^2}{n} - \frac{\left\{\sum xp - \frac{(\sum x)(\sum p)}{n}\right\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}}\right] \div (n-2)} \qquad (4)$$

Equations 1 and 2 define the position of a vehicle in a straight road segment; equation 3 gives information on steering drift across the lane (if there is any); and equation 4, along with the number of crossings of the direction of travel (or steering oscillations), provides a measure of the smoothness or stability of the ride.

If there were to be a radical change in the direction of the vehicle—and the most radical change that could occur while the vehicle remains in lane would occur if, for example, the vehicle first veered from the extreme right of the lane to the extreme left, then changed direction and veered from the extreme left back to the extreme right of the lane—then, the measures would indicate the radical change, since the steering instability would be relatively large but there would be only two steering oscillations.

The current experiment explored the driving performance of drivers while they were driving on straight and curved segments of expressway both before and after they had experienced traveling under automated control. Bloomfield and Carroll also demonstrate that it is possible to use this linear equation to describe the track of vehicle traveling around a horizontal curve as long as the position of the vehicle in the lane is determined relative to the cross-section of the lane.[14] When the road is curved and the position of the vehicle in the lane is determined relative to the cross-section of the lane, then at each moment, the position of the vehicle will be expressed relative to a line that is perpendicular to the tangent of the curve. In the current experiment, data were collected at a rate of 30 Hz. As a result, around every curve, there were series of tangents at 1/30-s intervals—each with a cross-sectional line that was perpendicular to it. The points at which the track of the vehicle intersected those cross-sectional lines, spaced 1/30-s apart, constituted the lane-position data.

To determine how the lateral position of the vehicle across the lane varies as it travels around a curve, the series of cross-sectional lines are considered together. Since the data were not collected continuously, but rather at intervals that were 1/30-s apart, there are segments of roadway between the cross-sectional lines where data were not collected, Note this is true whether the road is curved or straight. On a straight road, the segments where data are not collected are rectangular; on a curved road they are wedge-shaped. In either case, because the segments are so small when the data rate is as high as it was in this experiment, they can be ignored for purposes of statistical analysis. Because this is true, it does not matter for the analysis whether the roadway was straight or curved—a *linear* regression can be applied to the series of points indicating the position of the vehicle in the lane for both situations Therefore, the set of equations presented above could be used to derive the values of the lane-keeping and speed-control measures from the data collected in the current experiment.

A set of equations similar to those used to describe lane-keeping performance can be used to describe the driver's ability to control the speed of the vehicle. In this case, there are two speed control measures—the first is a measure of the velocity at any instant, the other a measure of whether the velocity is drifting higher or lower—and a measure of the stability of speed control. The speed-control stability measure can be used with the number of steering oscillations, i.e., the number of velocity reversals across the line of best fit (or velocity maintenance line). The equations used in this case differ in that p, a_{lk}, b_{lk}, and I_{lk} in equations 1, 2, 3, and 4 are replaced by v,

a_{sc}, b_{sc}, *and* I_{sc}, respectively, in equations 5, 6, 7, and 8. Equations 5, 6, and 7 provide a description of how well the driver maintains velocity, while equation 8 is a measure of smoothness or stability in maintaining velocity. These equations are presented below:

$$v = a_{sc} + b_{sc}x \tag{5}$$

$$b_{sc} = \frac{\sum xv - \frac{(\sum x)(\sum v)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \tag{6}$$

$$a_{sc} = \frac{1}{n}(\sum v - b_{sc}\sum x) \tag{7}$$

$$I_{sc} = \sqrt{[\sum v^2 - \frac{(\sum v)^2}{n} - \frac{\{\sum xv - \frac{(\sum x)(\sum v)}{n}\}^2}{\sum x^2 - \frac{(\sum x)^2}{n}}] \div (n-2)} \tag{8}$$

where:

- v is the velocity, indicated by the line of best fit, after the vehicle has traveled distance x.
- a_{sc} is the point at which the line of best fit intercepts the velocity axis at the start of the straight road segment.
- b_{sc} is the gradient of the line. If b_{sc} equals zero, the vehicle is traveling at constant velocity; if b_{sc} is positive, the velocity of the vehicle is gradually increasing; and if b_{sc} is negative, velocity is gradually decreasing.
- I_{sc} is the instability in velocity maintenance. It is an estimate of the extent of the velocity fluctuations that occur when the driver is attempting to maintain a chosen velocity.

APPENDIX 6: ANOVA SUMMARY TABLES

Appendix 4 contains the full summary tables for the eight ANOVA's conducted on the lane-keeping and velocity-maintenance performance measures, as well as minimum following distance. They are presented on the following pages in the same order in which they were discussed in section 3 of the main report.

Table 39. The ANOVA conducted to determine if the vehicle's steering instability was affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	0.03793604	0.01896802	1.42	0.2549
Age (A)	1	0.00046637	0.00046637	0.03	0.8530
IxA	2	0.01177371	0.00588686	0.44	0.6476
Subjects (Within AxI) [S (w/ A x I)]	39	0.52248338	0.01339701		
Data-collection Period (D)	9	0.07350458	0.00816718	3.68	0.0002
D x I	18	0.06807522	0.00378196	1.70	0.0372
D x A	9	0.02483198	0.00275911	1.24	0.2679
D x A x I	18	0.05897626	0.00327646	1.48	0.0961
D x S (w/ A x I)	331	0.73488368	0.00222019		

Table 40. The ANOVA conducted to determine if the vehicle's steering instability was affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	0.02838698	0.00946233	0.72	0.5465
Age (A)	1	0.00001410	0.00001410	0.00	0.9740
MxA	3	0.05433290	0.01811097	1.38	0.2647
Subjects (Within AxM) [S (w/ A x M)]	37	0.48636077	0.01314489		
Data-Collection Period (D)	9	0.08465011	0.00940557	4.03	0.0001
D x T	27	0.05987102	0.00221745	0.95	0.5403
D x A	9	0.01723823	0.00191536	0.82	0.5979
D x A x T	27	0.07037157	0.00260635	1.12	0.3186
D x S (w/ A x T)	313	0.73096976	0.00233537		

Table 41. The ANOVA conducted to determine if the vehicle's steering oscillations were affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	154.944891	77.472445	1.55	0.2259
Age (A)	1	10.9416453	10.9416453	0.22	0.6429
IxA	2	287.943700	143.971850	2.87	0.0685
Subjects (Within AxI) [S (w/ A x I)]	39	1954.20917	50.10793		
Data-Collection Period (D)	9	121.907063	13.545229	1.18	0.3096
D x I	18	261.645361	14.535853	1.26	0.2108
D x A	9	163.355854	18.150650	0.58	0.1212
D x A x I	18	130.339116	7.241062	0.63	0.8770
D x S (w/ A x I)	331	3812.96959	11.51955		

Table 42. The ANOVA conducted to determine if the vehicle's steering oscillations were affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	191.697600	63.899200	1.08	0.3694
Age (A)	1	11.7280261	11.7280261	0.20	0.6587
TxA	3	8.06935094	2.68978365	0.05	0.9869
Subjects (Within AxT) [S (w/ A x T)]	37	2188.47383	59.14794		
Data-Collection Period (D)	9	145.914110	16.212679	1.39	0.1910
D x T	27	333.466994	12.350629	1.06	0.3877
D x A	9	168.275905	18.697323	1.60	0.1129
D x A x T	27	238.211108	8.822634	0.76	0.8055
D x S (w/ A x T)	313	3647.71057	11.65403		

Table 43. The ANOVA conducted to determine if the vehicle's average velocity was affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	46.5404783	23.2702392	2.31	0.1125
Age (A)	1	63.8458253	63.8458253	6.34	0.0160
IxA	2	26.9691634	13.4845817	1.34	0.2738
Subjects (Within AxI) [S (w/ A x I)]	39	392.600108	10.066669		
Data-Collection Period (D)	9	6.04668251	0.67185361	0.59	0.8086
D x I	18	17.0744273	0.9485793	0.83	0.6678
D x A	9	10.3820630	1.1535626	1.01	0.4348
D x A x I	18	23.8519727	1.3251096	1.16	0.2971
D x S (w/ A x I)	331	379.535033	1.146632		

Table 44. The ANOVA conducted to determine if the vehicle's average velocity was affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	33.4259202	11.1419734	0.98	0.4134
Age (A)	1	73.0534443	73.0534443	6.41	0.0157
TxA	3	13.3031443	4.4343814	0.39	0.7613
Subjects (Within AxT) [S (w/ A x T)]	37	421.352701	11.387911		
Data-Collection Period (D)	9	6.11314316	0.67923813	0.59	0.8084
D x T	27	23.9744412	0.8879423	0.77	0.7946
D x A	9	8.98492123	0.99832458	0.86	0.5602
D x A x T	27	33.8329247	1.2530713	1.08	0.3605
D x S (w/ A x T)	313	362.753796	1.158958		

Table 45. The ANOVA conducted to determine if the vehicle's velocity drift was affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	0.00000109	0.00000055	0.28	0.7610
Age (A)	1	0.00000165	0.00000165	0.83	0.3675
IxA	2	0.00000430	0.00000215	1.09	0.3479
Subjects (Within AxI) [S (w/ A x I)]	39	0.00007731	0.00000198		
Data-Collection Period (D)	9	0.00001627	0.00000181	0.75	0.6630
D x I	18	0.00003718	0.00000207	0.86	0.6317
D x A	9	0.00002430	0.00000270	1.12	0.3476
D x A x I	18	0.00004479	0.00000249	1.03	0.4225
D x S (w/ A x I)	331	0.00079786	0.00000241		

Table 46. The ANOVA conducted to determine if the vehicle's velocity drift was affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	0.00000260	0.00000087	0.47	0.7019
Age (A)	1	0.00000245	0.00000245	1.34	0.2541
TxA	3	0.00001322	0.00000441	2.41	0.0823
Subjects (Within AxT) [S (w/ A x T)]	37	0.00006762	0.00000183		
Data-Collection Period (D)	9	0.00001616	0.00000180	0.74	0.6724
D x T	27	0.00005179	0.00000192	0.79	0.7647
D x A	9	0.00003440	0.00000382	1.57	0.1218
D x A x T	27	0.00006762	0.00000250	1.03	0.4249
D x S (w/ A x T)	313	0.00075985	0.00000243		

Table 47. The ANOVA conducted to determine if the vehicle's velocity instability was affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Intra-String Gap (I)	2	1.24801790	0.62400895	1.53	0.2291
Age (A)	1	1.06474962	1.06474962	2.61	0.1141
IxA	2	1.78103419	0.89051710	2.18	0.1261
Subjects (Within AxI) [S (w/ A x I)]	39	15.8967149	0.4076081		
Data-Collection Period (D)	9	15.6716798	1.7412978	10.70	0.0001
D x I	18	3.18585440	0.17699191	1.09	0.3629
D x A	9	1.70855007	0.18983890	1.17	0.3156
D x A x I	18	0.86336580	0.04796477	0.29	0.9981
D x S (w/ A x I)	331	53.8553963	0.1627051		

Table 48. The ANOVA conducted to determine if the vehicle's velocity instability was affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Transfer Method (T)	3	0.53418731	0.17806244	0.38	0.7671
Age (A)	1	0.90638186	0.90638186	1.94	0.1719
TxA	3	1.14709345	0.38236448	0.82	0.4919
Subjects (Within AxT) [S (w/ A x T)]	37	17.2815053	0.4670677		
Data-Collection Period (D)	9	16.9945637	1.8882849	11.66	0.0001
D x T	27	5.15758289	0.19102159	1.18	0.2503
D x A	9	1.67609982	0.18623331	1.15	0.3271
D x A x T	27	1.95279093	0.07232559	0.45	0.9930
D x S (w/ A x T)	313	50.6912463	0.1619529		

Table 49. The ANOVA conducted to determine if the vehicle's velocity fluctuations were affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	78.0377067	39.0188533	0.98	0.3848
Age (A)	1	62.4059711	62.4059711	1.57	0.2183
IxA	2	208.222086	104.111043	2.61	0.0862
Subjects (Within AxI) [S (w/ A x I)]	39	1554.84138	39.86773		
Data-Collection Period (D)	9	371.372852	41.263650	6.21	0.0001
D x I	18	146.440338	8.135574	1.23	0.2381
D x A	9	55.0193945	6.1132661	0.92	0.5071
D x A x I	18	167.701738	9.316763	1.40	0.1271
D x S (w/ A x I)	331	2197.70491	6.63959		

Table 50. The ANOVA conducted to determine if the vehicle's velocity fluctuations were affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	75.6116564	25.2038855	0.59	0.6275
Age (A)	1	7.3561323	97.3561323	2.27	0.1407
TxA	3	114.206754	38.068918	0.89	0.4571
Subjects (Within AxT) [S (w/ A x T)]	37	1589.12773	42.94940		
Data-Collection Period (D)	9	394.012074	43.779119	6.28	0.0001
D x T	27	144.317832	5.345105	0.77	0.7935
D x A	9	61.9044957	6.8782773	0.99	0.4506
D x A x T	27	184.696483	6.840610	0.98	0.4941
D x S (w/ A x T)	313	2181.18370	6.96864		

Table 51. The ANOVA conducted to determine if the minimum following distance was affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	52.4662146	26.2331073	0.12	0.8837
Age (A)	1	823.291303	823.291303	3.89	0.0558
IxA	2	637.040912	318.520456	1.51	0.2347
Subjects (Within AxI) [S (w/ A x I)]	38	8036.28097	211.48108		
Data-Collection Period (D)	1	349.899725	349.899725	7.38	0.0108
D x I	2	151.275862	75.637931	1.60	0.2195
D x A	1	2.27956905	2.27956905	0.05	0.8279
D x A x I	2	93.7251150	46.8625575	0.99	0.3839
D x S (w/ A x I)	30	1422.05591	47.40186		

Table 52. The ANOVA conducted to determine if the minimum following distance was affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	256.440777	85.480259	0.39	0.7637
Age (A)	1	782.678307	782.678307	3.53	0.0682
TxA	3	514.384220	171.461407	0.77	0.5161
Subjects (Within AxT) [S (w/ A x T)]	36	7972.54761	221.45966		
Data-Collection Period (D)	1	413.292087	413.292087	8.06	0.0083
D x T	3	153.817914	51.272638	1.00	0.4073
D x A	1	0.02237825	0.02237825	0.00	0.9835
D x A x T	3	76.1770967	25.3923656	0.50	0.6885
D x S (w/ A x T)	28	1435.49825	51.26779		

Table 53. The ANOVA conducted to determine if the vehicle's percentage of time in the center lane was affected by the data-collection period (D), the age of the driver (A), or the intra-string gap (I).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Intra-String Gap (I)	2	18757.6993	9378.8497	8.25	0.0010
Age (A)	1	11548.5120	11548.5120	10.15	0.0028
IxA	2	1863.11330	931.55665	0.82	0.4483
Subjects (Within AxI) [S (w/ A x I)]	39	44357.9937	1137.3845		
Data-Collection Period (D)	1	3206.43613	3206.43613	6.00	0.0189
D x I	2	625.980850	312.990425	0.59	0.5617
D x A	1	3.05523865	3.05523865	0.01	0.9401
D x A x I	2	3337.23474	1668.61737	3.12	0.0553
D x S (w/ A x I)	39	20850.6093	534.6310		

Table 54. The ANOVA conducted to determine if the vehicle's percentage of time in the center lane was affected by the data-collection period (D), the age of the driver (A), or the method of transferring control (T).

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	*p*
Transfer Method (T)	3	15483.2960	5161.0987	3.90	0.0161
Age (A)	1	11544.7243	11544.7243	8.73	0.0054
TxA	3	871.465356	290.488452	0.22	0.8821
Subjects (Within AxT) [S (w/ A x T)]	37	48917.2484	1322.0878		
Data-Collection Period (D)	1	4180.04300	4180.04300	6.94	0.0122
D x T	3	702.214251	234.071417	0.39	0.7617
D x A	1	12.3326149	12.3326149	0.02	0.8870
D x A x T	3	1867.43576	622.47859	1.03	0.3888
D x S (w/ A x T)	37	22271.9943	601.9458		

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